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Review of NUREG-0654, Supplement 3, “Criteria for Protective Action Recommendations for Severe Accidents”

Office of Nuclear Security and Incident Response

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Review of NUREG-0654, Supplement 3, "Criteria for Protective Action Recommendations for Severe Accidents"

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ABSTRACT

The Protective Action Recommendations (PAR) project provides an evaluation of alternative protective actions that could potentially reduce consequences during a severe radiological emergency at a nuclear power plant. The study included an assessment of alternative protective actions within a range of evacuation times and calculated public health consequences for these alternative protective actions. PARs identified in this report will aid in the determination of whether improvements or changes to the Federal guidance contained in NUREG-0654/FEMA-REP-1, Supplement 3 (NRC, 1996) would be beneficial. Early and staged evacuations provide alternative protective actions that have the effect of moving the public away from the source term in an expeditious manner. Many off-site response organizations already institute some level of early protective actions at a Site Area Emergency such as the movement of school children. Expanding on this concept with staged evacuations may reduce potential consequences and may better protect public health and safety under specific conditions. The effectiveness of the protective action strategy is sensitive to both initial release timing and the evacuation time, and therefore, it is important to reduce the uncertainties associated with each of these parameters. Volume I of this NUREG / CR provides the technical analyses of alternative protective actions. Volume II of this NUREG / CR will include a detailed assessment of the anticipated public response.

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EXECUTIVE SUMMARY

This Protective Action Recommendations (PAR) project has evaluated the current NRC PAR guidance contained in Supplement 3 to NUREG-0654 / FEMA-REP-1, Rev. 1, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants" (NRC, 1996) and assessed whether implementation of alternative protective actions could reduce potential health effects in the event of a nuclear power plant (NPP) accident. The consequence analyses modeled a hypothetical site with a uniform population density to support assessment of the relative benefits of alternative protective actions. Analysis was completed for three accident conditions including a rapidly progressing accident, a progressive accident and a no loss of containment accident. Any core damage accident is highly unlikely and rapidly progressing accidents are even less likely, but are included in the emergency preparedness planning basis. No absolute consequence numbers are to be inferred from this study. An early result of this project, based largely on the results of the research conducted on evacuation time estimates (ETEs) is that NRC is pursuing rulemaking to enhance ETEs.

Supplement 3 (NRC, 1996) provides guidance that licensees recommend evacuation of a 3.2 km (2 mile) ring and 8 km (5 miles) downwind for severe accidents with sheltering considered for unique instances such as severe weather. This PAR study demonstrates that sheltering is a better option under some circumstances. The study demonstrates that for rapidly developing, relatively high magnitude source terms, alternative protective action strategies are capable of reducing dose to the public (i.e., consequences). Based on this analysis, it would be beneficial to revise Supplement 3 to include more specific guidance on the use of sheltering. For more slowly progressing source terms radial evacuation works well, but there can be benefit through implementation of alternative protective actions. Several conclusions have been drawn from the PAR project, including:

- The study indicates that shelter-in-place followed by evacuation is more protective than immediate evacuation for rapidly developing releases.
- Evacuation should remain the major element of protective action strategies.
- Revision of NUREG-0654, Supplement 3, should be considered to better address the use of alternative protective actions.
- The study indicates that consideration should be given to protective action strategies that allow the population to quickly distance themselves from the plant, such as an early or staged evacuation, because this can reduce public health consequences.
- The study indicates that precautionary efforts during Site Area Emergency are prudent.
- The study indicates that strategies that reduce evacuation time can reduce consequences.
- The study and other ongoing studies indicate that special needs populations that do not reside in special facilities may be under served in evacuation planning. It appears that this issue warrants further investigation and development of guidance on this issue may be appropriate.

The effectiveness of protective actions is sensitive to both initial release timing of the source term and the evacuation time. It is therefore important to reduce the uncertainties associated with each of these calculations. For sites with short ETEs, evacuation is always the most appropriate recommendation, barring any constraints to implementation, such as adverse weather or damage to roadways from external events.

The conclusions from this study support the following protective action strategies when appropriately selected for an incident:

- Immediate radial evacuation,
- Shelter-in-place,
- Staged evacuation,
- Preferential sheltering for special needs individuals,
- Delayed evacuation, until traffic controls are in place,
- Early closure of schools, parks, government facilities, etc., at the Site Area Emergency, and
- Early notification of the general population within the 16 km (about 10 mile) Emergency Planning Zone (EPZ) to prepare for evacuation.

For rapidly developing radiation releasing events of relatively high magnitude and short duration, evacuation is the preferred protective action only if it can be completed in less than about 4 hours. Otherwise, sheltering-in-place until the plume has passed, followed by evacuation, results in fewer consequences. Protective action decisions are site specific as there are some sites with ETEs longer than 4 hours, but with very few people living within 8 km (5 miles) of the plant. For progressive events, some type of evacuation strategy would be the preferred protective action, barring any constraints to evacuation. In all cases, staged evacuation provides greater benefit than a standard radial evacuation, although in some instances this benefit was not pronounced.

Shelter strategies can keep the public out of the plume exposure path during the high concentration period, but sheltering must be followed by an evacuation to an area outside the EPZ. To determine whether evacuation or sheltering would be the best PAR, a calculation of the shelter time and subsequent evacuation is necessary. The time spent evacuating through a potentially contaminated area, combined with the shelter period, provides the information necessary to determine if this would be the most appropriate protective action. The benefits of sheltering diminish quickly if the subsequent evacuation is not optimized.

The results of the PAR study support consideration of revision of Supplement 3, NUREG-0654/FEMA-REP-1, Rev. 1, (NRC, 1996). This study confirmed, as stated in Supplement 3, that for all but a very limited set of conditions, prompt evacuation of the area near the plant is much more effective than sheltering the population in reducing the risk of early health effects in the event of severe accidents. A revision to Supplement 3 should consider addressing the following items.

- Clarification of the conditions for which shelter-in-place is effective.
- Guidance on the importance tracking the plume passage, communicating with those sheltered, and directing an effective evacuation immediately upon the termination of the shelter event.
- Emphasis on the benefits of staged evacuation.
- Guidance and expectations for the transit dependent persons.

If a revision to Supplement 3 is pursued, the effort would benefit from stakeholder input as it should foster development of protective actions that include the breadth of available options within the context of site specific considerations.

Volume I of this NUREG / CR provides the technical analyses of alternative protective actions, and Volume II will include a detailed assessment of the anticipated public response.

ACKNOWLEDGMENTS

There were many contributors to the completion of this study of alternative protective actions. NRC contributors included Randolph Sullivan who developed this project from concept and provided leadership and technical expertise throughout as well as managed the NRC administrative and budgetary requirements. Nader Mamish provided management vision and support over the multi-year schedule. Patricia Milligan and Steve LaVie provided technical insights supporting key elements of the project. Sandia National Laboratories contributors included Nathan E. Bixler who provided the consequence analysis modeling and Shawn P. Burns who provided the source term development work. Joseph A. Jones of Sandia was the project manager. Frank “Joe” Schelling and Lori Dotson of Sandia supported the development of the alternative protective actions and performed the analysis of the data. The guidance of David Kunsman in understanding the complexities of probabilistic risk analysis as well as NUREG-1150 is particularly acknowledged. Steve Nowlen and Frank Wyant provided valuable insight regarding developments in fire probabilistic risk assessment. Dana Powers provided a technical review of this study and a review of recent developments in radionuclide release physics. John Forester, Randall O. Gauntt, Scott Ashbaugh, Eric Klamerus and Marcos Modesto also provided valuable insights and important recommendations for additional literature to include in this work.

ACRONYMS

ACH	air exchange rate per hour
BWR	boiling water reactor
CDF	core damage frequency
CFF	Containment Failure Frequency
CSEPP	Chemical Stockpile Emergency Preparedness Program
EAS	Emergency Alert System
EF	early fatalities
EP	emergency preparedness
EPA	Environmental Protection Agency
EPZ	emergency planning zone
ETE	evacuation time estimate
FEMA	Federal Emergency Management Agency
FSAR	final safety analysis report
GE	general emergency
IAEA	International Atomic Energy Agency
IEF	Initiating Event Frequency
IPE	individual plant examination
ISLOCA	interfacing system loss of coolant accident
ITS	intelligent transportation system
KI	potassium iodide
LCF	latent cancer fatalities
LOCA	loss of coolant accident
LOSP	loss of site power
LP & SP	low power & shut down
MACCS2	MELCOR Accident Consequence Code System Version 2
mph	miles per hour
NEI	Nuclear Energy Institute
NCF	no-containment failure
NG	noble gas
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PAR	Protective Action Recommendation
PS	preferential sheltering
PWR	pressurized water reactor
RCS	reactor coolant system
REM	roentgen equivalent man
SIP	shelter-in-place
TEDE	total effective dose equivalent

1.0 INTRODUCTION

1.1 Background

The requirement for nuclear plant licensees to develop a range of protective actions for the 16 km, (about 10 mile) plume exposure EPZ, including evacuation, sheltering and consideration of potassium iodide (KI) is established in 10 CFR 50.47(B)(10). The capability to appropriately recommend protective actions is inspected during NRC evaluated emergency preparedness biennial exercises, and is tracked as a Performance Indicator within the Reactor Oversight Process. This requirement extends beyond EPZ, on an *ad hoc* basis, should that contingency ever be necessary. The regulatory basis for reasonable assurance that the public health and safety can be protected is based, in part, on NRC oversight of the licensee's capability to make appropriate and timely PARs.

The NRC Emergency Preparedness (EP) program establishes criteria for emergency response planning in NUREG - 0654 / FEMA - REP - 1, Rev. 1, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants" (NRC, 1990). Within NUREG - 0654, a range of protective actions is developed for the plume exposure pathway EPZ for emergency workers and the public. Since the publication of NUREG - 0654, extensive studies of severe reactor accidents have been performed which clearly indicate that for all but a very limited set of conditions, prompt evacuation of the area near the plant is much more effective in reducing the risk of early health effects than sheltering the population (NRC, 1996). NRC published Supplement 3 to NUREG-0654 / FEMA-REP-1, Rev. 1, "Criteria for Protective Action Recommendations for Severe Accidents," dated July 1996 ("Supplement 3") to provide emergency response organizations the benefit of the insights gained from the severe accident studies and to assist them in improving their emergency response capabilities.

In the case of severe reactor accidents, Supplement 3 to NUREG - 0654 / FEMA - REP - 1, Rev. 1 (NRC, 1996) would have licensees preferentially recommending evacuation within a 2-mile radius and five miles downwind, in lieu of sheltering. NRC has reinforced the guidance contained in Supplement 3 through outreach, training, and inspection. As a result, licensees have largely accepted the guidance, but as an unintended consequence, some licensees have restricted the consideration and use of sheltering, as evidenced in the design of their initial and follow-up notification forms.

NRC staff reviewed the guidance in Supplement 3, and determined a need for further investigation of alternative protective actions. The review and investigation of alternative protective actions conducted for this study includes consideration of the following:

- Early evacuation is the best option when there is time to move people before a release begins. However, this may not be the best option in some scenarios, as there are considerations that may make sheltering or other strategies more appropriate.
- The PAR regimen should be reviewed for its use and appropriateness during a "rapidly evolving" emergency. In this case, immediate shelter-in-place may be more appropriate than evacuation.

- The establishment of local shelters that would afford more protection than normal homes has not been given in-depth consideration. Schools, government buildings, and commercial buildings can offer significant protection as demonstrated in their use as shelters for natural hazards and in the Chemical Stockpile Emergency Preparedness Program (CSEPP, 1996, 2001). These types of structures may be only minutes away from the affected population, whereas evacuation travel time to a location outside of the 10-mile EPZ could be significantly longer.
- The most severe public health consequences are estimated to result from narrow plumes, as this concentrates radioactive nuclides. However, consequences from such narrow plumes may be avoided by moving short distances at right angles from the plume. There may be issues associated with the recommendation and implementation of such a strategy, since the technique has not been evaluated for its applicability and use in emergency situations.

Some of these considerations may depend on the relative density of the population distribution and the design of the supporting transportation infrastructure. Furthermore, their relative importance to the reduction of consequences and other considerations may be dependent on the ETE. The possibility of evacuating the public located within the 10-mile EPZ of nuclear plants has received considerable attention. Some stakeholders in high population density areas have voiced concerns that evacuation may be difficult to accomplish in a timely manner. These concerns have highlighted the need to ensure that NRC guidance for PAR development consider the appropriateness of sheltering and other protective action strategies in response to certain scenarios. To address practical issues of implementation, stakeholders were involved in early planning activities as well as in discussions on detailed implementation aspects of the alternative protective actions considered. The States of Virginia, New Jersey, and Illinois volunteered to support the NRC in discussions on this project and provided valuable input.

1.2 Objectives

The objective of this project is to evaluate the current NRC PAR guidance contained in Supplement 3 to NUREG-0654 / FEMA-REP-1, Rev. 1, and assess whether implementation of alternative protective actions could reduce potential health effects in the event of a NPP accident. To achieve this objective, an evaluation of alternative protective actions has been conducted. These alternative protective actions have been evaluated in consideration of the following elements which could affect protective action planning and/or implementation:

- Technological advances within emergency preparedness,
- A spectrum of nuclear plant accidents,
- Improvements in accident progression understanding,
- The "post-9/11 threat environment",
- Improvements in ETE,
- Additional sheltering strategies,
- Additional evacuation strategies,
- "Rapidly evolving" accident scenarios, and
- Improvements in dose projection techniques.

NRC, in coordination with the Federal Emergency Management Agency (FEMA) will use the results of this study to determine if a revision to Supplement 3 is warranted.

1.3 Scope

The scope of this project includes activities necessary to perform comprehensive evaluation of the current NRC PAR guidance for protective actions. The project is divided into two phases, each documented in a separate volume for this NUREG / CR. Volume I includes the selection of the source term, identification of alternative protective actions to be assessed and the consequence analyses. Volume II includes an assessment of likely public reaction for the population that resides within EPZs. This assessment addresses nuclear power plant emergency response planning and preparedness and the public's willingness or ability to implement protective actions as directed.

The following Volume I activities were conducted to complete this study:

- A comprehensive literature review;
- Selection of accident scenarios and source terms;
- Review of technological advances that affect protective action development;
- Determination of the efficacy of the alternative protective action strategies;
- Analysis of protective action implementation issues;
- Assessment of studies of public behavior in response to emergencies; and
- Development of this Volume I report which includes the summary and conclusions from the research and analyses conducted.

Volume II includes a comprehensive assessment of expected public behavior in response to an accident at a nuclear power plant and an assessment of the expectations of emergency responders. The Volume II sociological assessment includes:

- Conducting public focus group interviews with members of the public to assess their knowledge of potential emergency response protective actions and their anticipated response to protective actions in the event these may ordered. Discussions include alternative protective actions to understand the public's potential response to these alternatives.
- Conducting focus groups with emergency response management and personnel to gain information from these responders on their expectations during a response to an accident at a nuclear power plant.
- Conducting a national telephone survey of residents living within EPZs. A telephone survey instrument will be developed with input from the Volume I activities. Approximately 800 completed surveys will be obtained and a statistical analysis of the data will be performed to provide quantitative results on the expected response of the public to alternative protective actions.
- Development of Volume II to this NUREG/CR.

2.0 APPROACH

To accomplish the Volume I and Volume II scope of activities, an organized technical approach was developed. The following Volume I activities were conducted in this comprehensive assessment of alternative protective action strategies:

I. A detailed review of literature and technical documentation on protective action planning and implementation was conducted. An assessment of emergency response planning and response experience for non-nuclear incidents was also included on a limited basis to support completeness of this study. The relevant information and data gained from the literature is integrated within this study and is referenced where applicable. The extensive list of references used to support this research is included in Section 9.0 and may be of use to others performing emergency planning research.

II. Source terms were selected for use in the consequence analyses by conducting a review of the spectrum of accidents that can result in the need for protective actions. Using information gained from this review, a suite of reactor accidents was developed that are General Emergencies, using information contained in Nuclear Energy Institute (NEI) 99-01 as the standard emergency classification scheme (NEI, 2003). An assessment was conducted of the accidents considered "rapidly evolving" or "severe", in the terminology of NUREG - 1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, Final Summary Report" versus those considered to be "not severe" or where there is time (e.g., four or more hours) to consider and prepare for protective action implementation. This activity was accomplished using existing accident progression analyses, such as NUREG-1150. Where a frequency was not known, a qualitative manner was used. There was no attempt to quantify the frequency of terrorism-based events; however, this is considered in the alternative PAR strategies. There was also no attempt to update source term magnitude or frequency data relative to the individual plant evaluations. The purpose of the source terms selected for this project is to support the consequence modeling, and these are not intended to represent source terms for any specific plant.

III. Technology advancements were evaluated to determine if such advances might improve the planning and implementation of protective actions. The information gained in this evaluation was included in the consequence assessment. Advances and improvements were assessed in the areas of:

- Evacuation time estimate technologies;
- Dose projection techniques;
- Public notification methods; and
- Evacuation dynamics understanding.

IV. Consequence modeling was then conducted to determine the efficacy of alternative protective action strategies in terms of reducing consequences from severe accident plumes. Parameters that were studied in the consequence analyses included:

- Timing of off-site release compared to the ETE;
- Reduction in consequences for sheltering or evacuation versus plume type;
- Timing of release versus public notification time;
- Duration of sheltering period for various types of shelter;
- Alternative evacuation strategies, e.g., lateral evacuation and staged evacuation;
- Sheltering in typical housing;
- Sheltering in preferential shelters that offer greater shielding benefits;
- Efficacy of sheltering versus evacuation for various ETE values; and
- Efficacy of sheltering as an initial action followed by evacuation.

V. An analysis of protective action implementation issues was completed to assess the viability of those alternative protective action strategies modeled in the consequence analysis. The protective action strategies evaluated include:

- Radial evacuation;
- Lateral evacuation;
- Staged evacuation;
- Shelter-in-place followed by radial evacuation;
- Shelter-in-place followed by lateral evacuation;
- Preferential sheltering followed by radial evacuation; and
- Preferential sheltering followed by lateral evacuation.

VI. Upon identification of alternative protective actions that had potential for inclusion in the emergency preparedness program, an effort was made to understand the behavioral psychology and sociology applicable to evacuees. This assessment of published literature provides input into the Volume II focus group and telephone survey activities and includes determination of:

- Likely public acceptance of alternate sheltering strategies;
- Likely public acceptance of alternate evacuation strategies;
- Best methods to communicate advanced PAR strategies to the public; and
- Whether other sociological factors should be considered in the development of PAR strategies.

VII. After completing the above activities, a summary and conclusions on the viability of implementing alternative protective actions as a means to reduce potential health effects is presented.

Stakeholders were involved in early planning activities as well as in discussions on detailed implementation aspects of the alternative protective actions considered. This involvement was included to support assessment of the practical issues of implementation. The States of Virginia, New Jersey, and Illinois volunteered to support the NRC in discussions on this project. Members of cognizant agencies participated in meetings and conference calls to discuss the project approach and potential alternatives considered. These agencies included emergency management, health and safety, radiological agencies as well as first response organizations such as the State Police departments. The information gained from this participation provided valuable input into the assessment of the alternative protective actions.

The following sections of this report provide the data and analysis used in assessing the alternative protective actions. The structure of this report follows the approach identified above with each section building upon the previous section.

3.0 SOURCE TERM DEVELOPMENT

3.1 Source Term Analysis

The evaluation of alternative protective actions requires a decision on the source term or source terms to be used in the analyses. Credible source terms are necessary to support the decisions on whether alternative PARs should be considered. As stated earlier, any core damage accident is highly unlikely and rapidly progressing accidents are even less likely, but are included in the emergency preparedness planning basis. The approach to establishing the source terms to be used began with a detailed review of NUREG-1150 (NRC, 1990a) followed by a review of updated information related to source terms and accident frequency (NRC, 1988a; NRC, 1993; NRC 1994a,b; NRC 1995a,b; NRC 1997 a,b,c; NRC 2000; NRC 2001; NRC 2004). The analysis included review of data contained in NUREG-1150 and its supporting documents (NRC, 1990b; NRC, 1990c; NRC, 1990d; NRC, 1990e; NRC, 1990f; NRC, 1989) regarding events requiring PARs for the fleet of NPPs to support the selection of credible source terms for use in the MELCOR Accident Consequence Code System Version 2 (MACCS2) consequence modeling.

3.2 Source Term Selection

The selection of a realistic source term for examination in the PAR project represents a technical challenge. The timing, energy, and radionuclide release fractions which characterize the source term represent a complex combination of severe accident phenomenology which is further complicated by the details of the initiating event and overall plant damage state. The effort required to evaluate the frequency of rapidly progressing severe accident events in some generic way appropriate to the PAR study and develop the associated quantitative source term data using modern accident progression models is far beyond the scope and resources available to this study. It is also unrealistic, at the opposite extreme, to select release magnitudes and durations for the various important radionuclide groups without regard to accident phenomenology while maintaining the integrity of the overall PAR analysis.

As an alternative, the Severe Accident Risk (NUREG-1150) Study (NRC, 1990) funded by the NRC in the late 1980s provides an extensive accumulation of source term data from an array of severe accidents associated with both pressurized water reactors and boiling water reactors. A fair criticism of the NUREG-1150 information is that it represents out of date modeling and simulation technology; however, it should be remembered that the primary focus of the PAR study is on the release timing relative to the start of evacuation. The details of the release magnitude and duration are unlikely to have a dramatic impact on the conclusions of this study as long as the values used are correct to within an order of magnitude. To make this point concrete, sensitivity studies were conducted to evaluate the impact of the release magnitude and duration on the PAR results.

In addition to the NUREG-1150 study some consideration was also given to low power and shut down (LP&SD) operations (NRC, 1993). Despite the much lower reactor power and relatively short duration of LP&SD operations, studies of the Surry and Grand Gulf sites (NRC, 1990c, NRC, 1989) indicate that events during these operations may be risk significant relative to power operations. This is largely due to unisolated containment and the unavailability of various safety systems during LP&SD operations. Early fatalities resulting from LP&SD operations may be decreased however due to the decay of short-lived radionuclide species including iodine and tellurium.

Figure 3.1 summarizes the release timing and relative frequency associated with site specific source terms at the Surry, Sequoyah, Grand Gulf, Peach Bottom, and LaSalle sites. The information is drawn largely from NUREG-1150 and the supporting site analysis reports as well as more recently published studies relating to severe accidents at light water reactor plants (NRC, 1992b). Each interval on the ordinate of Figure 3.1 represents an order of magnitude change in source term frequency. The values have been omitted from the ordinate of Figure 3.1 to emphasize the out-of-date nature of the NUREG-1150 data. While the relative frequency of the different events summarized in Figure 3.1 may be valid, and sufficient for the purposes of this study, the absolute magnitude of event frequencies taken from NUREG-1150 are doubtful. It is also important to note that the release timings shown in Figure 3.1 are relative to the warning time as specified in the NUREG-1150 report.

From the standpoint of the PAR study, the most interesting source terms are the high frequency rapidly progressing source terms in the upper left hand corner of Figure 3.1. Figure 3.2 provides an expanded view of the rapidly progressing, high frequency portion of Figure 3.1. For the purposes of selecting representative source terms for use in the PAR study a number of source terms shown in Figure 3.2 were selected for additional consideration. These source terms are indicated by a box in Figure 3.2.

A comparison between the noble gas and halogen release timings for each of the source terms indicated in Figure 3.2 is provided in Figure 3.3 and Figure 3.4 respectively. The release magnitude given on the ordinate of Figure 3.3 and 3.4 indicate the fraction of the core inventory released per second. The two source terms selected for use in the PAR study are shown in bold in Figures 3.3 and 3.4 and indicated by arrows in Figure 3.2. The details of each source term are provided in Appendix A. These source terms were selected largely based on the fact that they start within four hours of warning time and represent at power accident sequences. The other rapidly progressing events shown in Figures 3.3 and 3.4 corresponded to a low power and shut-down sequence and was screened from selection given the low release energy and smaller core inventory typically associated with low power and shut down conditions. The sequences in Figures 3.3 and 3.4 are identified as follows:

- ST-1: Surry Interfacing System LOCA;
- ST-2: Surry LP&SP with Early Containment Failure;
- ST-3: LaSalle Fire with Early Containment Failure;
- ST-4: LaSalle Fire with Venting;
- ST-5: LaSalle Transient with Venting;
- ST-6: LaSalle with Early Containment Failure; and
- ST-7: Sequoyah LOCA No Containment Failure.

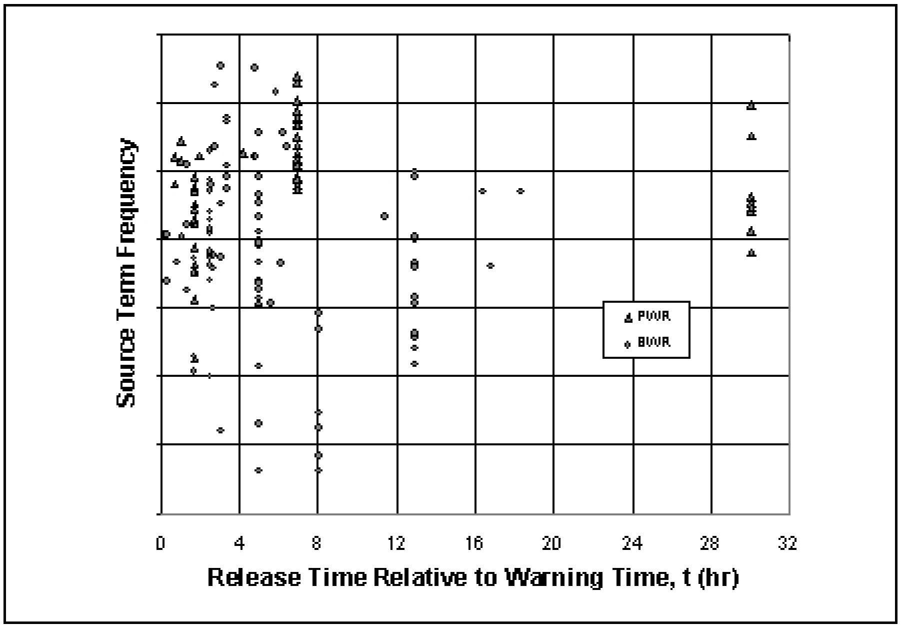

Figure 3.1 - Release time corrected to warning time associated with site specific source terms for the Surry, Sequoyah, Grand Gulf, Peach Bottom, and LaSalle light water reactor sites due to internally and externally initiated events.

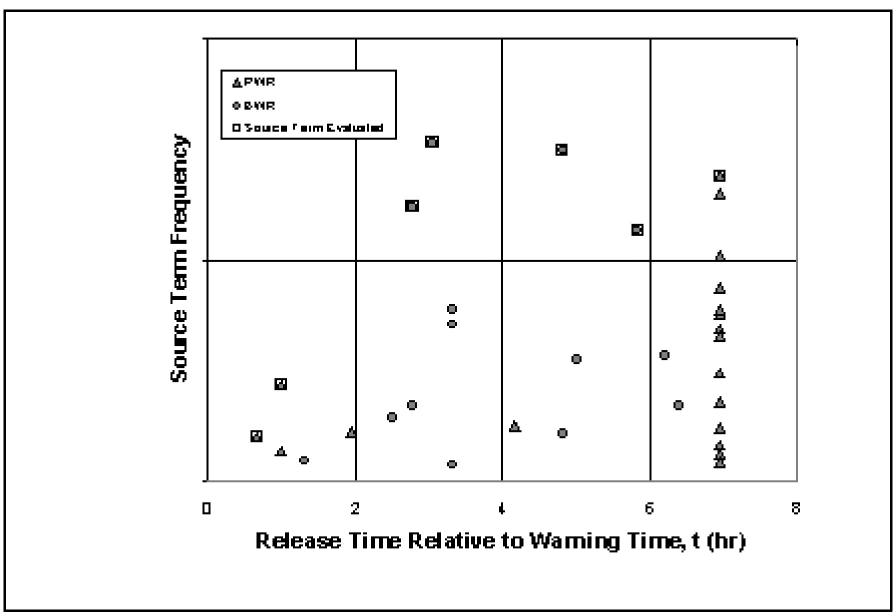

Figure 3.2 - Higher frequency short time scale source terms for internally and externally initiated events at Surry, Sequoyah, Grand Gulf, Peach Bottom and LaSalle. Boxes indicate those source terms evaluated for potential use in the protective action recommendation study.

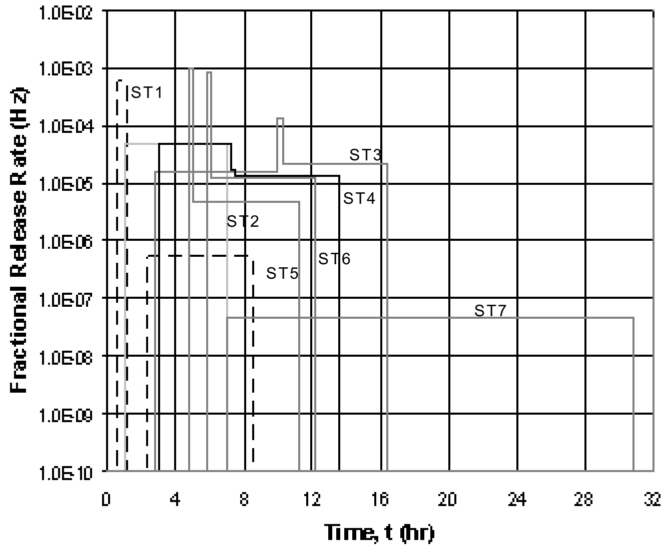

Figure 3.3 - Noble gas releases associated with highest frequency and shortest time scale source terms at Surry, Sequoyah, and LaSalle.

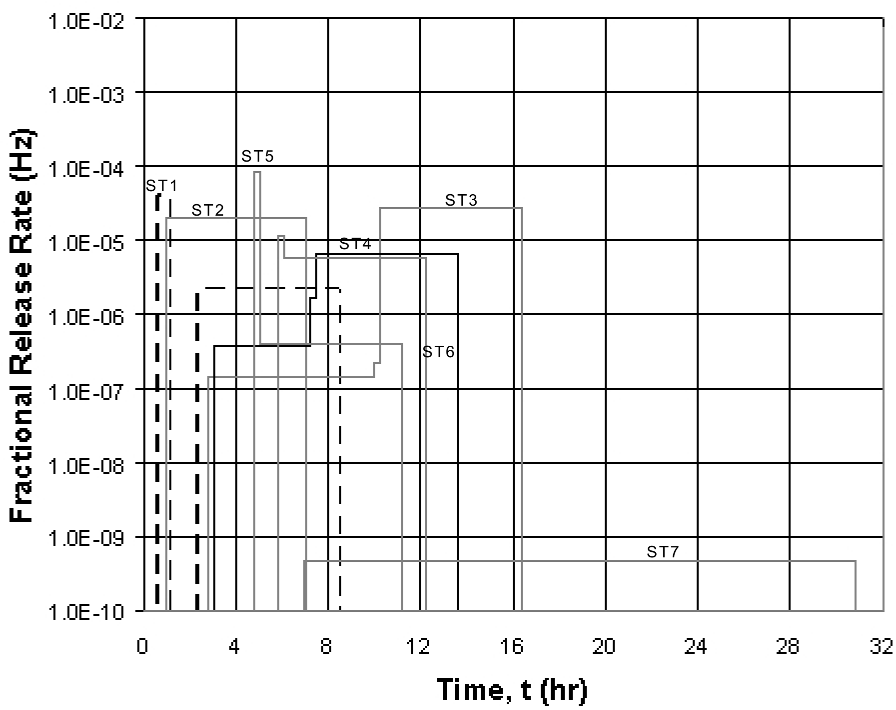

Figure 3.4 - Halogen group releases associated with highest frequency and shortest time scale source terms at Surry, Sequoyah, and LaSalle.

3.3 Frequency and Relative Event Magnitude Discussion

Although the "warning time" varies to some extent based on the details of the event, it corresponds in general to the initiation of core damage. However, current emergency action level definitions do not necessarily correlate general emergencies with the onset of core damage. For example, in the case of loss of site power (LOSP) events, the emergency action level definitions provided by NEI 99-01 call for the declaration of a general emergency when site power is lost for an extended period of time rather than when core damage occurs (NEI, 2003). Since the source term frequencies implicitly assume core damage has occurred, it is instructive to consider how these frequencies may compare to the frequencies of general emergencies defined in NEI 99-01.

It is difficult to obtain frequency data for the general emergencies described in NEI 99-01 directly but it is possible to consider the frequency of initiating events that are common between the reactor sites considered in the NUREG-1150 documentation. In this way it is possible to develop a qualitative feel for the frequency of potential general emergencies relative to the corresponding core damage and containment failure frequencies.

The initiating event frequency information is drawn from the NUREG-1150 site risk analysis reports for LOSP events as well as various loss of coolant accident (LOCA) events and is summarized in Figure 3.5. The horizontal bars in Figure 3.5 represent the range of initiating event frequencies and corresponding core damage and containment failure frequencies for LOSP and LOCA events for the Surry, Sequoyah, Grand Gulf, and Peach Bottom reactor sites. The frequency ranges represent the range of mean frequencies across these sites.

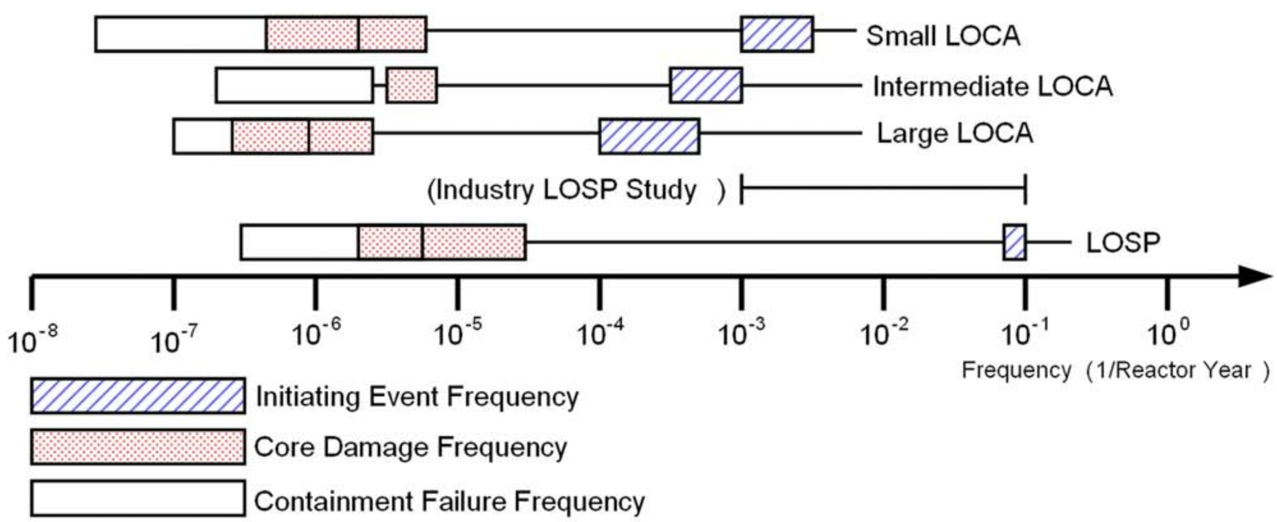

Figure 3.5 - Ranges of initiating event frequencies and corresponding core damage and containment failure frequencies for LOSP and LOCA based on NUREG-1150 site risk analysis reports for the Surry, Sequoyah, Grand Gulf and Peach Bottom reactors.

While the relative frequency of the different events summarized in Figure 3.5 may be valid, and sufficient for the purposes of this study, the absolute magnitude of event frequencies taken from NUREG-1150 are doubtful. An important observation from Figure 3.5 is that the core damage frequencies for the events shown are two to four orders of magnitude smaller than the corresponding initiating event frequencies. Containment failure frequencies are an additional order of magnitude smaller than the core damage frequencies. A qualitative view of these relative magnitudes is provided in Figure 3.6 where the area of the outer box represents the frequency of initiating events and the area of the inner most box represents the containment failure frequencies.

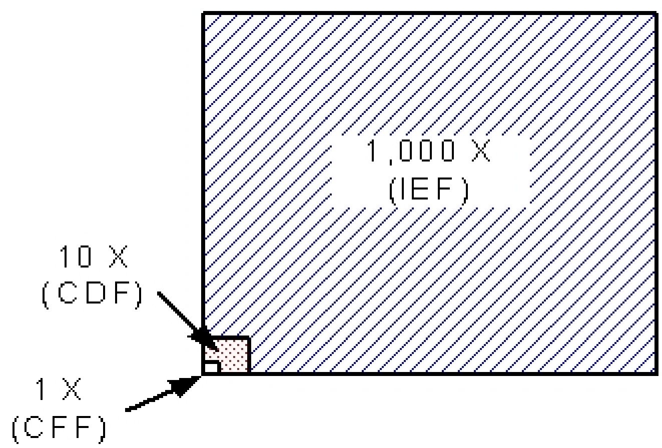

Figure 3.6 - Relative magnitudes of Initiating Event Frequency (IEF), Core Damage Frequency (CDF), and Containment Failure Frequency (CFF) for LOSPs and LOCAs based on NUREG-1150 site risk analysis reports for the Surry, Sequoyah, Grand Gulf and Peach Bottom reactors.

In other words, general emergency declarations based on initiating events may be several orders of magnitude more frequent than general emergency declarations based on the initiation of core damage.

4.0 TECHNOLOGICAL ADVANCES AND EMERGING IMPROVEMENTS IN EVACUATION PLANNING

4.1 Introduction

This section investigates technological advances of systems as well as emerging improvements in the emergency response community that may affect the performance of alternative protective actions. There is an ongoing emphasis within the emergency response community to improve response capabilities in many areas. New technologies are being developed and emergency response agencies are continuously striving to implement ideas, concepts, training, and technologies to mitigate consequences. Some areas of advancement include computer-related hardware and software, communication devices, analysis tools and training.

Emerging technologies, capabilities, and other considerations are identified where possible to provide information that may be considered in development of protective actions. The following elements of emergency response were reviewed to determine the potential effects on protective action decisions.

- Traffic management;
- Evacuation time;
- Dose projection;
- Public notification;
- Evacuation dynamics; and
- Other areas important to public evacuations.

4.2 Traffic Management

Improvements in traffic management have the potential to improve the evacuation of the public out of the EPZ. Opportunities to improve the efficiency of an evacuation such as improving roadway capacity or reducing traffic demand should be considered in the development of emergency response plans. Two specific areas of interest include intelligent transportation systems (ITS) and communication with evacuees.

Technological advances have been made in ITS, and these systems are now available and operating in many communities (ITS, 2002). ITS vary in application and capability, and when integrated in an emergency response plan, can provide relief in the level of manpower and equipment necessary to manage traffic in an emergency. Common ITS technologies and other communication techniques have been demonstrated effective in evacuations, such as the evacuation for Hurricane Katrina.
These technologies include:

- Video surveillance, such as traffic cameras;
- Dynamic message signs or variable message signs;
- The 211, 311 and 511 telephone-based traveler information systems (available in most states);
- Highway Advisory Radios; and
- Use of Internet-based traveler information systems.

An advantage of using ITS is that the information provided to the evacuating public can be current. Dynamic message signs can be programed and messages changed remotely from a traffic management center to reflect current status. The information received by emergency response personnel from the ITS, such as video feedback, is real-time. This allows an efficient emergency response to situations that are delaying an evacuation, such as unanticipated accidents or bottlenecks. Resources may then be mobilized to mitigate the cause and improve the traffic flow in these areas. Mobilizing additional support during a large scale evacuation is difficult and may require creative means and preplanning to effectively deploy into congested areas. Components of ITS are operable in most areas of the U.S., including rural locations, although they are not always utilized at the full capabilities.

Integration of ITS can support traffic management activities; however, fundamental actions such as manning key intersections during evacuations still provides one of the most effective methods of managing traffic. Development of a traffic management plan should include assessment of the transportation network as a system to identify where ITS may be integrated. To the extent practical, the traffic management plan may be tested to determine time required to implement traffic control and to assess the effectiveness of the traffic control system.

Communication with evacuees is during the evacuation provides a form of traffic management and may include information on what to expect with the evacuation activities such as road closures, diversions, or contra flow operations. Additionally, communication with those members of the public who should not evacuate can be equally important for successful traffic management. Effective communication with those not instructed to evacuate can help reduce a shadow evacuation which may reduce the evacuation time for the affected area. Existing systems such as the Federal Communications Commission implementation of nationwide codes for non-emergency use (FCC, 1997) can be utilized to support these communication needs. A 211 code is available and frequently coordinated with the United Way to provide information to individuals during an emergency. A 311 code is available and used in many states for non-emergency police and other government services. The 511 code is designated for traffic and transportation information. With many individuals having cell phone availability these nationwide codes can be readily accessed by individual as they are in the process of evacuating.

Although the telephone contact numbers are increasing, telephone use is usually discouraged during large scale emergencies, thus, having many communication options can potentially have an adverse impact if the communication system becomes stressed. These systems have been demonstrated as a valuable resource during the evacuation for Hurricane Rita in 2005, but the systems do rely on the telephone network as well as the State or local agency to update the information. Because these telephone services require individual action to call the phone number, other more proactive methods that reach out to the evacuees should also be integrated into the communication plan. These additional methods of providing information include highway advisory radio, news broadcasts, and other means that reach those individuals who do not utilize the telephone resources.

4.3 Evacuation Time

Evacuation is a core element of emergency response planning for NPPs and reducing the evacuation time may reduce consequences. If an evacuation can be conducted prior to the arrival of the plume, it is 100% effective in reducing consequences. Reducing evacuation time reduces potential consequences in a severe accident. This is one of the items assessed in the consequence analyses conducted in the next section.

As an element of emergency response planning, the licensee prepares an estimate of the time to evacuate the affected sectors of the plume exposure area under a variety of conditions. The EPZ roadway network and evacuation input data are modeled using commercial software which provides a suite of evacuation times for the planning scenarios evaluated. Advancements in these modeling tools provide a valuable opportunity to perform more detailed analyses for emergency planning. These tools allow the user to simulate traffic control conditions, infrastructure improvements, or modify other assumptions to determine the associated evacuation time based on the selected conditions. The detailed assessments can be used to identify sensitivities in the ETEs and can be used to determine if there are opportunities to reduce evacuation time.

Traffic simulation and evacuation analysis tools have rapidly advanced in the last decade and are readily available to support virtually all aspects of evacuation planning and evacuation time estimating. Many of these tools are described in NUREG / CR-6863, “Development of Evacuation Time Estimates for Nuclear Power Plants” (NRC, 2005a). Traffic simulation and analysis models offer advantages for emergency planning and may be used to evaluate:

- Optimum traffic control plans;
- Benefit of infrastructure improvements, such as new roadways, intersection modifications, etc.;
- The benefit of traffic control options; and
- Sensitivity analyses to determine the important parameters and better understand the uncertainty in the model.

Evacuation time estimates are planning tools and as such, there is no maximum time for evacuation specified although NUREG - 0654 / FEMA - REP - 1, Rev. 1, Appendix 4, does require identifying specific recommendations for actions that could be taken to significantly improve the evacuation time (NRC, 1996). The ETE is factored into the protective action decisions based on the specific conditions at the time of an incident.

For large population sites, the investigation required to develop an ETE may be very complex. Ten years ago, only a small number of commercial companies prepared ETEs and the methodologies used were similar. With the advancements in this field there are now many different computer models available to calculate ETEs, and licensees may hire consultants or perform the calculations in-house. In development of ETEs, it is important that the sensitivities of the computer models and input parameters be understood by those who work with these models and interpret the results. This was one of the conclusions of “The Sensitivity of Evacuation Time Estimates to Changes in Input Parameters for the I-DYNEV Computer Code” (NRC, 1988b) which identified that ETEs are sensitive to both changes in the input parameters as well as the characteristics of the transportation network. The study further suggests that use of the model be limited to analysts familiar with the code. Sensitivity in the ETE calculation was also shown in an analysis of evacuation time estimates in a North Carolina hurricane area (Perkins, et al., 2001). In this study it was determined that the optimum evacuation time occurred if buses were mobilized within 10 minutes of receipt of the evacuation warning. As the mobilization time increased to 40 minutes, the en-route travel time increased by 141% demonstrating the sensitivity of parameters.

Decision makers may use the ETE information when considering protective action decisions regarding whether or not an evacuation should be implemented. In development of existing ETEs, input parameters and assumptions may vary depending the site and the technical expert developing the ETE. Consistency in parameter development and oversight of quality control on these parameters may reduce uncertainty in ETEs. An early result of this project, based largely on the result of the research conducted on ETEs, is that NRC is pursuing rulemaking to enhance ETEs.

4.3.1 Evacuation Time When Using Shelter Strategies

Modeling may also support understanding of the evacuation time when shelter strategies are included in the protective action. The protection offered by sheltering can be substantial by keeping the public out of the plume exposure pathway during the time when the radioactive concentration of the plume is high. In a severe accident, sheltering would be followed by an evacuation. The ETE has historically been calculated only for evacuations; however, to best determine whether evacuation or sheltering is the most appropriate protective action, emergency planning activities could include a calculation of the shelter time and subsequent evacuation. The time spent evacuating through a contaminated area, combined with the shelter period, provides the information necessary to determine if this would be the most appropriate protective action.

Evacuation time following a shelter event may not be the same as the evacuation time for an incident in which there is no shelter period; however, the methodology is applicable and much of the data is already acquired during emergency planning development of the ETE. When the order to evacuate is given, after a shelter period, it may be assumed that the vehicle loading of the roadway network may be more immediate than the normally distributed loading that is assumed for a standard radial evacuation. This more immediate loading may affect the evacuation time. Specific considerations for shelter strategies include:

- Means and ability to communicate with the sheltered public;
- Termination plan for sheltering;
- Mobilization time to leave the shelters; and
- Evacuation time estimate parameter changes.

To be effective, shelter strategies must include a means of ending the shelter event by notifying the public when to leave and what direction to travel. The timing of the shelter termination is important to minimize dose to the public. As the plume passes over the shelters, contaminated particulate material and radioactive gases may penetrate into the shelters. The amount of contamination and radiation that enters the shelter is relative to the tightness and shielding of the shelter; however, some contamination and radiation will enter most shelters. Pressurized facilities may prevent interior contamination; however, these facilities are typically for chemical hazard zones, and for this study, it is assumed that pressurized facilities would not be available.

Implementing a shelter strategy provides residents time to prepare to evacuate as soon as an order is issued. This will result in a more immediate loading of the transportation network. Some differences in calculating the evacuation time estimate for this strategy include fewer background vehicles on the roadway network, lack of a shadow evacuation which may be controlled or complete prior to the end of the shelter, and the more immediate loading of the roadway network.

4.4 Dose Projection

Some advancements to the MACCS2 model used in this study are currently planned for completion in the near future. These advancements may provide better understanding of dose projection and may support improved decisions on protective actions in future analyses. Dose calculations in this report are performed using MACCS2 to simulate the impact of accidental atmospheric releases of radiological materials on the surrounding environment. The principal phenomena considered in MACCS2 are atmospheric transport using a Gaussian plume model, short-term and long-term dose accumulation by a number of pathways. Changes that may affect the understanding of PAR development and implementation from improvements in dose projection include:

- Improvements in uncertain parameters;
- Input of evacuation speed and direction by grid element;
- Increasing the number of cohorts;
- Alternatives to the linear, no-threshold model; and
- Long-range lateral plume spread and plume rise.

MACCS2 previously allowed ring by ring specification of the initiation of sheltering and evacuation. It also allowed three evacuation phases for which evacuation speed can be specified. A recent improvement to MACCS2 in 2007 allows the input of evacuation speeds and direction for each grid element to provide a more realistic representation of the evacuation process. This will be especially valuable when individual sites are being studied as opposed to a hypothetical site such as that considered in this PAR study.

For this project, MACCS2 was limited to three emergency response cohorts. Consistent with NRC practices, two of these were used to represent the large fraction of the population who evacuate and the small fraction of the population who do not. Recent improvements in 2007 have increased the number of cohorts which may now be used to represent a distribution of the population who evacuate at different times. This improvement will provide a more realistic view of the actual evacuation process.

Four optional long-term health effects models are now available in MACCS2: (1) the traditional linear, no-threshold model; (2) an annual threshold model, which can use a different threshold for each subsequent year, as suggested in the Environmental Protection Agency’s Protective Action Guidelines; (3) a lifetime dose threshold in addition to the year-by-year dose threshold, as given in the Health Physics Society position; and (4) a multiplicative factor in the form of a set of piecewise-linear segments that cover the entire dose-response range.

An improved model for plume buoyancy has been added to MACCS2 in the area of plume modeling and was used in these calculations. This model predicts lofting of an energetic plume that is less dense than the surrounding air. The second model is for long-range plume dispersion, as recommended by Hanna (2002), and is based on a time rate of expansion of the plume instead of the distance-based approach that had been used in MACCS2.

The above improvements to MACCS2 will provide additional realism to the calculations to support consequence analyses. Although some of these improvements were completed prior to the completion of the PAR project, the calculations supporting the PAR project were performed prior to the release of the MACCS2 version that incorporates these improvements.

4.5 Public Notification

Advancements in public notification methods can provide more immediate awareness to the public of the hazard and can provide a more direct means of instructing the public on the protective action to be followed. Public notification methods have improved with the increasing capabilities of telecommunication devices and services, and with use of the Internet. In review of "An Analysis of Evacuation Time Estimates Around 52 Nuclear Power Plant Sites, Vol. 1 & 2," NUREG / CR-1856 (NRC, 1981), and in review of more current ETEs, evacuation times can exceed 20 hours under certain conditions and frequently exceed 8 hours for the public under normal conditions. The ability to notify the public promptly is important and improvements that can support notifying the public faster can only benefit the emergency response.

Information is disseminated to residents of EPZs and is provided in the form of brochures, calendars, utility bill inserts, or in the front pages of the phone book, etc. The information packets typically contain instructions for evacuation and sheltering along with information for special needs population groups, such as those dependent on public transportation. An underlying assumption in emergency planning is that residents who receive these materials are familiar with the emergency information. Most sites use these notification packages to elicit information on individuals with special needs to identify this segment of the population that may require transportation.

Internet websites are also used to provide additional information such as the Massachusetts Emergency Management Agency website that provides information on preparedness for a nuclear emergency as well as emergency information calendars for Pilgrim, Seabrook, and Vermont Yankee nuclear power plants. Utility and State emergency management web sites provide emergency response updates which may include specific evacuation routes for use during an event. This is to supplement the limited information that can be disseminated through the brief Emergency Alert System (EAS) message and serves as a confirmation for those who desire such. These websites are not intended to replace other information distribution, but to supplement these when appropriate.

Notification methods that have historically been used in emergencies have not been formally updated to consider the effect of the internet. For instance, many emergency response planning brochures request that the individual refrain from using the telephone to assure adequate phone lines are available for the emergency responders. Then, the brochure provides a web address for further information during an emergency. The computer access to the web address very often requires use of a telephone line.

The structure is in place to assure notification is provided; however, it is necessary that the notification is received and understood by residents for it to be effective. Effective warnings within the EPZ should reach, in a timely fashion, every person at risk who needs and wants to be warned, no matter what they are doing or where they are located (National Science and Technology Council, 2000).

Sirens are the primary initial means of public notification, with the exception of some isolated areas. In some areas where more direct warning is needed, alternative means to notify the public are implemented. These may include:

- Single station alert radios or tone alert radios that warn residents and businesses to tune their radio or television to an EAS station for information on the event;
- Door-to-door or route alerting which includes use of a public address system from a vehicle. This method is typically used as a backup or secondary method in an NPP event and is conducted by emergency response personnel. Route alerting has been identified as the most effective means of communication in non-nuclear related evacuations (NRC, 2005b).
- Alerting devices in special facilities such as nursing homes, schools, industrial plants, etc.; and,
- Reverse 911 type systems that telephone residential numbers within the EPZ and provide a recorded message. These systems have proven effective and are rapidly increasing in use. There are some limitations including the need to maintain current phone numbers for the targeted population area. Also, residents must be educated to listen to the emergency message so they do not hang up when they hear the start of a recorded message. The systems often encounter telephone messaging machines. Lastly, some households have unlisted numbers or no longer use land line phones instead relying on cellular phones. Communities that use these reverse 911 systems usually provide a means to register cell phones or unlisted numbers for use with notification system.

As suggested by FEMA (FEMA, 1985) the alert and notification method for special facility populations (i.e., schools, hospitals, etc.) and transient population groups (i.e., recreational facilities, etc.) should be analyzed on a case-by-case basis. This is commonly performed within EPZs, and in some communities the administrative procedures require notification of these population groups through direct telephone contact.

4.6 Evacuation Dynamics

In the assessment of evacuation dynamics for natural disasters, technological hazards, and malevolent acts, many factors have been identified that influence the behavior of the public during a response to an emergency. With the heightened awareness of malevolent acts, more recent studies have been performed, providing additional insight into evacuation dynamics and the reaction of the public in response to hazards. One of the most relevant factors identified is that ‘in general’ the population follows the instructions provided by the decision makers (NRC, 2005b). Discussions of relevant studies and sociological issues are provided in this section and a more detailed analysis of evacuation dynamics will be provided in Volume II of this report.

Evacuation dynamics has been integrated into early planning documents, such as NUREG-0654 / FEMA-REP-1, Rev.1 (NRC, 1980) and NUREG / CR-4831 (NRC, 1992a), along with others. These reports identify basic evacuation dynamics considerations such as the differences in population groups and guidance on the development of trip generation times. An assessment of evacuation dynamics is provided herein for the three population groups identified in Appendix 4, NUREG-0654 / FEMA-REP-1, Rev.1 (NRC, 1980) including permanent residents, special facilities, and transients.

There is very limited data and experience with nuclear emergencies, thus dynamics of the public response to natural disasters, technological hazards, and malevolent acts provide the primary basis for assessment of the dynamics of a response to a hazard requiring implementation of a PAR. An extensive literature review was conducted to gain insight into actual and predicted responses to evacuations.

4.6.1 Literature Review

Effective implementation relies on the public receiving a warning and responding as planned. There are differing opinions on whether past experience and past research on other types of disasters provides a useful guide for predicting how people will behave in a General Emergency involving release of radioactive materials. The academic community tends to be somewhat divided, with more traditional disaster researchers arguing that people generally behave in an orderly, rational fashion in disasters, and this is how they will behave in a radiological emergency. However, some researchers who have focused more specifically on events involving toxic materials argue that traditional disasters and an emergency involving an NPP are different and public reaction will be different. Extrapolating from "conventional" situations and assuming that the public will respond in a similar manner to a malevolent nuclear event may be a high-risk approach. While it is often difficult to predict how a population might behave under these circumstances, there is a general agreement among researchers that the decision of people to evacuate is influenced by the following four factors:

- The individuals belief and understanding of the evacuation warning;
- The level of the perceived risk to the individual;
- The existence of an evacuation plan or other means to protect the individual; and
- The desire and ability to evacuate as a family unit.

In general, public cooperation with established evacuation procedures depends on the public's level of confidence in the evacuation plan and the process. Perry (1985) looked at volcanic eruptions, floods, and nuclear power plant emergencies and noted that the human response was similar for each event. While, the public's perceived threat of harm from nuclear power plants was much greater than for the other disasters, Stallings (1984) found that the voluntary evacuation at Three Mile Island did not differ significantly from evacuations due to natural disasters.

Zelinsky and Kosinski (1991) confirmed a commonly held belief that evacuees tend to move in the direction that minimizes or cancels the effect of the disaster. Furthermore, Helbing et al. (2002) found that people have a strong aversion to taking detours or moving opposite to the desired walking direction, even if the direct way is crowded. Zelinsky and Kosinski (1991) in their study of 27 military, natural, and industrial disasters between 1937 and 1986, found evidence to support the following commonly-held evacuation beliefs:

- Evacuees are more likely to stay with friends and relatives than public shelters;
- Families tend to evacuate as a unit;
- Women, children, and the infirm are more likely to evacuate than able-bodied working-age males; and
- Families with children are more likely to evacuate than childless families or single individuals.

Zelinsky and Kosinski found evidence that some people may not evacuate and others could ‘linger’ near their homes for a while after the warning to evacuate. The 2005 NRC study on large scale evacuations, (NRC, 2005b) found that a portion of the public refused to evacuate in half of the 50 cases they studied, although this generally amounted to less than one percent of the affected population.

Zeigler and Johnson (1984), as well as Johnson (1984), concluded from their research that the public would over-respond (i.e., shadow evacuations) to evacuation orders in the event of a nuclear power plant accident. Sorensen (1986) questioned those results and suggested that evacuation response is dictated by awareness of risk, personalization of that risk, evaluation of alternative actions, and then deciding a course of action. Sorenson (1986) did not believe that there would be significant shadow evacuations. The NRC study on large scale evacuations (NRC, 2005b) found that shadow evacuations occurred in 36% of the 50 cases studied. Of those cases involving shadow evacuations, traffic movement was impacted in only a few large scale natural disaster evacuations. However, if there is a significant shadow evacuation, there is the potential for increased evacuation time.

Zelinsky and Kosinski (1991) found that the risk of death or injury during evacuation is less than that incurred by remaining in place during the disaster period. This finding was confirmed by NUREG / CR-6864 (2005b) that showed that in 50 evacuation cases studied, people were safely evacuated from the area, lives were saved, and the potential number of injuries was reduced. Sorensen (1986) also found that in 293 evacuations due to chemical accidents between 1980 and 1984, there were no reported injuries due to the evacuations, but several injuries due to the hazard.

Recent evacuation studies including NUREG / CR-6864 (NRC, 2005b) and previous studies by other researchers such as Fischer (1994, 1998a, 1998b); Keating (1982), Perry (1985), and Sorensen (1986) found that, in general, the public did not panic during an evacuation. The evacuations associated with the September 11, 2001 attacks, the evacuations of Manhattan during the summer power outage of 2004, and the more recent evacuations in the aftermath of Hurricane Katrina were all large scale. In these incidents, there was a high degree of cooperation among the public and no large scale panic reported.

Lasker (2004) conducted a telephone survey of 2,545 randomly selected households and asked questions related to a biological terrorist event (smallpox) and a radiological terrorist event (i.e., a dirty bomb). The results revealed that only 60% would shelter-in-place for as long as told in the event of a dirty bomb; 20% would not fully cooperate in the dirty bomb situation and would leave the shelter of their building to take care of their children, other family members, or because they felt safer elsewhere; and 40% did “not trust what the government said” or did. One should note that this survey was based on how the public “said” they would respond as opposed to their “actual” response under such circumstances.

4.6.2 International Guidelines

International guidelines do exist for emergency planning, but national procedures and practices differ in some areas due to national habits, cultural specificity, and societal needs (IAEA, 1997). Different national procedures and practices, in the case of a radioactive release affecting two neighboring countries, may lead to different decisions in the implementation of countermeasures (OECOD, 2003). Review of international approaches to emergencies showed similarities in many areas to those of the United States. For notification and warning, most countries use a combination of warning sirens, public address systems, and media alerts to instruct the public on the protective action. Other general response actions, including implementation of traffic control to prevent entrance into the plume area and distribution of potassium iodide, are similar to U.S. emergency response. Furthermore, most countries recognize that special arrangements are necessary for schools, hospitals, and other special facilities. One item not found in any of the reviewed international literature was the development of evacuation time estimates.

4.6.3 Permanent Residents

Permanent residents include all people having a residence in the area, other than special institutions, such as hospitals, nursing homes, prisons, etc. (NRC, 2005a, 1992a). For scenarios in which this population group is at home or work, it can be reasonably assumed that, upon hearing the warning sirens, or other warning mechanism, they will determine relatively quickly that it is an actual emergency. However, when people are away from the planning area (i.e., not at home or work) the expected response to the warning may not be as obvious. The evacuation dynamics are then affected because the time to receive, comprehend, and act may be longer than the time considered in the emergency planning. The dynamics of permanent residents may be more uncertain in other scenarios where the residents are not at home when the warning is initiated.

A clear understanding of the emergency and clear direction on what to do reduces uncertainty in the public response. As alternative PAR strategies are developed, scenarios regarding the proper course of action and means of communicating such actions need to be considered. For example:

- Residents may not be at home when sirens are sounded and clear direction can assist them in understanding how to respond. For instance, individuals may be in their vehicles, at local restaurants, shopping centers, attending special events, etc., These individuals need clear direction to help them decide whether to return home or evacuate out of the EPZ.
- Some EAS messages state that during a shelter-in-place protective action, residents should take the potassium iodide that has been provided. Directions may be better understood if communication includes instructions to those who are not residents, such as tourists, and to individuals who may not have or may not know the location of their potassium iodide. Those that do not have potassium iodide available may not understand whether it is still appropriate for them to shelter. This is State specific as some States stockpile KI and would distribute the KI at reception centers.
- Residents follow direction from emergency responders when the direction is clear and understood. In a general emergency caused by a malevolent act, some of the emergency responders may be redeployed to assist with other aspects of the emergency and may not be available to immediately establish traffic control along the evacuation route. Without clear and direct guidance through traffic management, the public may not evacuate along the most optimal routes identified in planning.
- Residents with pets require guidance on what to do with their animals. Guidance is typically provided in emergency planning brochures, but this guidance varies by site and ranges from leaving the animals at home with food and water to bringing them to the congregate care center where animal control will assist with further arrangements. Brochures for most sites state that pets are not allowed at congregate care centers. With each new large scale

evacuation in the U.S., it is more evident that people place a high family value on their pets, and in some instances refuse to evacuate if they can not bring their animals. On October 6, 2006 the "Pets Evacuation and Transportation Standards Act of 2006" was signed into law amending the Stafford Act to ensure that State and local evacuation plans address the evacuation of pets. Although this is recognized as an issue, and has been addressed through Federal regulation, the emergency planning brochures that provide the evacuation instructions to individuals have not been updated and are not always clear on the evacuation of pets.

- Many parents can be expected to pick up their children from school. Although this is discouraged in many EPZs, the desire to evacuate as a family unit is strong and should not be overlooked. Many of the emergency response planning brochures that are distributed to the residents of EPZs state that children will be evacuated from school and parents should meet them at their designated congregate care center. Although most States will close schools and evacuate children at Site Area Emergency or earlier, it is expected that parents will receive word of the evacuation through formal or informal channels. Such societal notification is real and may be anticipated. Evacuation planning could address this issue through enhanced awareness and planning for parental response. This may include planning for additional traffic around schools to accommodate parents.
- Evacuation of the population dependent on public transport requires developing site specific information on the number of persons requiring transportation, any specialized needs, and the number of vehicles, drivers, and special assistance needed to transport this population group out of the EPZ. This population group includes (NRC, 2005a) but is not limited to:

    - Households with no vehicles;
    - Households with one vehicle that is at work and will not return;
    - Households with minor children at home alone;
    - Households dependent on specialized transportation, such as wheelchair vans or ambulances; and
    - Business commuters using public transport or those who bike, run, or walk significant distances to work.

A subset of the permanent resident population group that are those individuals with special needs that do not reside in special facilities. An attempt is generally made within EPZs to identify this population through distribution of registration cards along with the annual information package, though the registration response rate is generally low. Complicating registration is the reluctance of individuals to identify themselves as having special needs. This reluctance to register has been confirmed through discussions with emergency planners and some of the reasons provided for not registering include:

- An assumption that someone (friend or family) will be willing to assist them
- Some individuals are sensitive to their disability or their need for assistance
- Some individuals are concerned about the security of the data; and
- Some individuals simply do not realize they are in the special needs population.

There are Federal requirements on the management and distribution of health related information which affects the compilation and distribution of such data. In Linn County Iowa, the Linn County Emergency Management Agency has implemented a proactive registration effort working with various service groups to help educate individuals on completing registration cards. Since the beginning of this proactive effort, the number of special needs individuals registering for assistance has almost doubled.

The population dependent on public transportation need to be informed of any limits on personal belongings. Evacuation instructions in most emergency planning brochures state to bring provisions for a few days. It can be assumed that some persons could have substantial carry-on items, including household pets, medical supplies, and other accessories. In the evacuation of Galveston, Texas prior to Hurricane Rita, over 4,000 people used public buses in the evacuation. In discussions with emergency response personnel who supported the evacuation, the capacity of each bus, when loaded with evacuees and their belongings, was approximately 50% of the rated capacity. Planning for the use of buses should include assessing the capacity and consideration of the time for loading and unloading. In areas where the public transport may not arrive for lengthy periods of time, the public should be informed on what to do as they wait, as well as how to determine when the public transport will arrive at their designated pickup location. Detailed and sound assumptions should be documented in ETEs when calculating the time for return trips and should include delays that may be encountered when traveling against the prevailing evacuating traffic.

Informing the public of particular actions to take in the event that they are within the EPZ and hear the warning sirens, but are not at their place of residence, may alleviate confusion. Clear guidance could be provided on whether individuals that are at local restaurants, shopping centers, or performing other daily activities within the EPZ, should return home, stop at the nearest building, or evacuate out of the EPZ. For shelter-in-place, it may be reasonable to define immediate implementation requirements such as stay in place or stop at the nearest building and take shelter.

4.6.4 Special Facilities

Special facility residents include those confined to facilities, such as hospitals, nursing homes, prisons, etc. Schools are included in the segment of special facilities (NRC, 1980). During development of emergency planning and ETEs, these facilities are identified and considered as a separate population group for purposes of assessing protective action needs, and calculating the ETE. Facilities are identified individually along with any special resource needs, such as number of buses for schools, ambulances for hospitals, and other transportation needs. Because of the added detail in preplanning, special facilities are expected to be prepared to receive the warning, react promptly, and respond according to plan.

Some special facilities, such as schools, may receive early warning through direct notification during an emergency. This preplanned activity ensures that the special facilities are notified immediately and directly to allow reaction and response activities to begin in a timely manner. Special facilities may also have specific evacuation and shelter plans. When a warning is issued, these facilities are generally well prepared to receive the warning and respond.

A reasonable planning assumption is that special facilities will respond to the warning very quickly. Although the warning may be direct and the facility response immediate, the nature of these facilities requires additional time to implement a protective action strategy, and thus, an immediate reaction does not necessarily result in a fast response. Each special facility is unique and should be addressed on a case-by-case basis that includes consideration of peak populations in the facilities. Many facilities have local evacuation plans and are prepared to implement the plans. Evacuation times for special facilities (e.g., hospitals) may be as long as, or longer than, the evacuation time for the general public and have been estimated at more than 20 hours depending on the special facility population, number of special facilities affected, available resources to evacuate the facilities, and number of return trips required.

In the evacuation of special facilities for Hurricanes Katrina and Rita, it was determined that many of the facilities had independent evacuation plans. As such, these plans frequently identified the same ambulance or bus service to support a facility evacuation. When all of the facilities required evacuation, there were not enough resources to support all of the facilities. Dependence on common resources could be investigated during the emergency response planning to assure adequate resources are available for the entire EPZ.

4.6.5 Transient Population

The transient population includes tourists, employees not residing in the area, or other groups that may visit the area (NRC, 1980). As stated earlier, the public tends to follow direction in an emergency; however, the transient population group may receive less direction due to their location at the time of the warning. As with the other population groups, if there is not a clear understanding of the emergency, uncertainty in response may be higher.

Evacuation behaviors of the transient population differ in several ways from people who receive evacuation notices in their home communities (Drabek, 1996). Tourists and transients are more likely to receive evacuation warnings from hotel employees or facility staff. Tourists are considered visitors that may not have any familiarity with the potential hazard or the protective action requirements. Transients are generally individuals that may have traveled into the EPZ to work or shop or perform other daily activities and likely would have familiarity with the area. Because this information is secondhand, rather than directly from the mass media, transient groups often have less time to act on warning notices and likely have no knowledge of suitable evacuation routes. Evacuation planning should include a means to communicate specific information to the transient populations. In EPZs where there are large beach populations or amusement parks with thousands of tourists, the public needs to be informed of the action expected. They may need to know whether they should return to their hotel and pack, then evacuate, or immediately leave the EPZ. These factors point toward potentially different responses by transient populations than by area households and these differences should be considered in the development of the PAR strategies especially where there is a large transient population present within the EPZ.

4.7 Other Areas Important to Alternative PAR Strategies

In determining the benefits of alternative protective actions, several other elements are considered. In evacuation, shelter, or other PAR strategies, the public will spend some time inside a vehicle or other structure. Typically, dose calculations provide little or no credit for dose reduction. This has been based on older studies of vehicles, where little or no protection was observed (Peterson and Sabersky, 1975). However, more recent studies involving newer vehicles have shown that a closed vehicle with the ventilation closed provides some level of protection to the occupants. Studies supporting the Chemical Stockpile Emergency Preparedness Program (CSEPP, 1990) and Department of Homeland Security programs have determined newer vehicles have a greater protection factor than older models studied previously. Although all of the studies evaluated used a noble gas model (i.e., no particulates, agglomeration, or settling), the concept of a vehicle offering some level of protection was validated. To realize the benefit from these newer and less pervious vehicles, instructions could be provided to the public to keep vents and windows closed during an evacuation where a release is present or imminent.

4.8 Summary of Technological Advances and Emerging Improvements

An early result of this project, based largely on the result of the research conducted on ETEs is that NRC is pursuing rulemaking to enhance ETEs. As described above there are many areas in which new technologies, advancements in technologies, and improved understanding of evacuation dynamics that support emergency response planning. Integrating these new tools and lessons learned can lead to improved planning for nuclear emergencies within EPZs. The following provides a summary of these advances and emerging improvements.

Traffic Management

Use of ITS has been demonstrated to provide improved communication to evacuees during an evacuation. It is also important to communicate with individuals who should not evacuate. This may reduce shadow evacuations or other voluntary evacuations of individuals not affected by the hazard.

Evacuation Times

Evacuation remains a primary protective action in emergency planning and any efforts that can reduce evacuation time will benefit the emergency response. Emergency planning can utilize evacuation modeling to investigate improvements in evacuation times with some suggestions identified below:

- Population growth may be assessed to determine when evacuation times may change significantly;
- Roadway and infrastructure improvements can be assessed to determine where improvements may improve the evacuation; and
- Sensitivity analyses may be conducted to determine those elements that are sensitive to change as well as where to focus efforts to reduce evacuation times.

The ETE provides a key element in NPP emergency preparedness programs because decision makers may use the ETE information when considering protective action decisions. Defining the specific criteria by which elements of the ETE will be reviewed and requiring the submittal of the modeling input data files would help in assuring that the estimates are reasonable and are developed following a sound basis.

Dose Projection

Planning improvements in MACCS2 include enhancing the network evacuation model to allow user friendly input of direction and speed for each grid element. The ability to model additional cohorts in MACCS2 has also been incorporated into the model. A recommended improvement to MACCS2 is the connecting of precipitation with evacuation speed. Currently this requires the calculations to be set up manually.

Public Notification

Protective action orders are conveyed using a variety of methods such as EAS messages, route alerting, reverse 911 systems, etc. Additionally, systems such as web based information systems and Statewide telephone numbers for non-emergency use such as 211, 311 and 511 are in place. These methods provide a means for potential evacuees to confirm the hazard as well as obtain additional information on response requirements. When considering these types of systems, the capacity of the telephone network must be understood. Many emergency response planning brochures still state that evacuees should refrain from using the telephone to free up lines for the emergency response. For the local and State planning basis, it may not be reasonable to request that the public refrain from using the telephone during an emergency. The public may be expected to rely on telephones and cell phones to confirm evacuation information and to ensure family members are aware and preparing to evacuate.

Evacuation Dynamics

Studies of recent large scale evacuations have provided valuable insights on the evacuation of the permanent population, special facilities, and the transient population. These lessons learned can be integrated into emergency response planning guidance documentation. Specifically, evacuation planning can be improved by including some of the following suggestions:

- Permanent residents that are in an affected area should be clearly instructed on what protective action to take while permanent residents that are near the incident, but not within an affected area should also be provided clear instructions not to evacuate.
- Special facilities have existing evacuation plans; however, in Hurricanes Katrina and Rita in 2005, it was discovered that many of these facilities rely on the same resources to support an evacuation. When all of the facilities needed to evacuate at the same time, there were not adequate resources to support the evacuation. An integrated assessment should be conducted during emergency planning to assure that necessary resources are available to support evacuation needs.
- The transient population group may need more detailed direction during an emergency since they may not be familiar with the area. If a sheltering PAR is ordered, the transient population may not know where to shelter. The unique considerations for the transient population group should be considered in the development of the PAR strategies especially where there is a large transient population present within the EPZ.
- The population that is dependent on public transportation requires added detail in emergency response planning to assure all members of this population group are identified and adequate resources are available to support their evacuation.
- Individuals with special needs who do not reside in special facilities may be under served although an attempt is generally made within EPZs to identify this population. Experience with large scale evacuations has shown that there is inadequate planning for this segment of the population. Improvements in identifying this population group and securing the resources necessary to support the evacuation should be included in emergency response planning for EPZs.

Evacuation dynamics were reviewed with this project to identify information on potential public response to an incident in order than emergency managers may consider adjustments in planning, where appropriate, to address elements of the expected response. Many of the emergency response planning brochures that are distributed to the residents of EPZs were reviewed during the course of this project. These brochures usually state that children will be evacuated from school, and parents should meet them at their designated congregate care center. It can be expected that many parents will attempt to pick their children up from school. Although this may be discouraged, the desire to evacuate as a family unit is strong and can be planned for during an incident.

5.0 CONSEQUENCE MODELING

5.1 MACCS2 Parametric Study

A parametric study was conducted using MACCS2 consequence model to determine the benefits of alternative protective action strategies in reducing consequences. MACCS2 was developed at Sandia National Laboratories for the NRC for use in probabilistic risk assessments for commercial nuclear reactors to simulate the impact of accidental atmospheric releases of radiological materials on the surrounding environment. The principal phenomena considered in MACCS2 are atmospheric transport using a Gaussian plume model, short-term and long-term dose accumulation through several pathways (including cloudshine, groundshine, inhalation, deposition onto the skin, and food and water ingestion), mitigative actions based on dose projection, early and latent health effects, and economic costs. The following phenomena can be incorporated within a single calculation:

- Release characteristics;
- Meteorological sampling;
- Atmospheric dispersion and deposition considerations;
- Exposure pathways and duration;
- Protective actions and dose mitigation;
- Movement of population as cohorts;
- Individual and population doses; and
- Health and economic consequences.

The goal of the MACCS2 parametric study is to determine the relative advantages of each of the alternative protective action strategies in terms of reduced early and latent health effects. The alternative strategies are compared with the baseline evacuation protective action to assess relative performance. Specific parameters studied include:

- Timing of off-site release vs. public notification time;
- ETE values of 4, 6, 8, and 10 hours;
- Source terms;
- Shelter-in-place;
- Preferential sheltering (PS);
- Radial evacuation;
- Lateral evacuation; and
- Adverse weather (precipitation).

The results of the consequence analyses are presented in terms of early and latent fatalities and are provided in Appendix B, MACCS2 Results. The tabulated results in the appendix are normalized to the total sum of the early and latent fatalities to present the relative benefits of the alternative protective actions considered. Normalized values are used in the comparison because this project addresses reactor sites in general rather than any specific reactor sites. The early fatalities represent the population that would receive a dose large enough such that there would be a probable death within one year of exposure. The latent cancer fatalities represent the delayed health effects causing death over the lifetime of the exposed individuals.

5.2 Modeling Choices

Standard MACCS2 modeling for NRC assessments uses the parameters in Sample Problem A which is discussed in the MACCS2 user's manual (NRC, 1998). For consistency with NRC modeling practices, many of the MACCS2 input parameters used in this study are identical to those in Sample Problem A. The following input parameters differ from those in Sample Problem A:

- The KI ingestion model is used in this study. This model assumes that 50% of the population ingests KI during the optimum ingestion period and that ingesting KI produces a 95% reduction in thyroid dose from inhaled radioiodine. The 50% value was selected because the effectiveness of KI is dependent upon the time at which KI is ingested prior to any potential exposure. If KI is not taken at the precise time, the effectiveness diminishes. Because it is possible people may take the KI outside of the optimum timing window for effectiveness or may have difficulty locating their KI, a 50% value was used.
- A 16-km (10-mile) radius is used as the outer boundary for dose calculations. For radial evacuation, members of the population travel directly toward this boundary and receive no further dose after they cross it. For lateral evacuation, members of the population travel azimuthally (around the compass) until they emerge from the plume (Figure 5.1). The plume width is a function of distance from the reactor site and atmospheric stability class. Thus, the lateral distance traveled before an individual receives no further dose is variable.

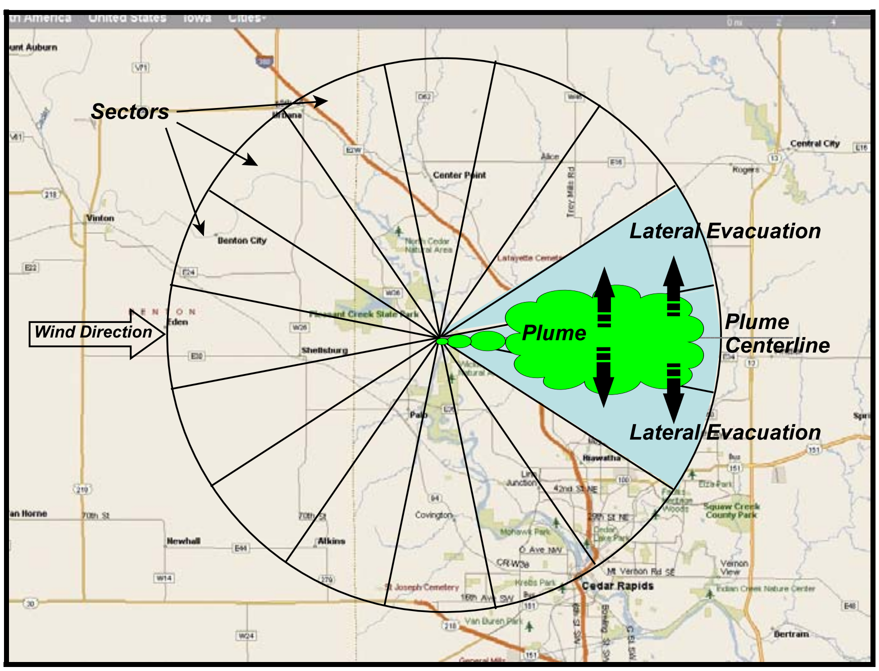

Figure 5.1 - Lateral evacuation in MACCS2 modeling.

- The delay to shelter for the SIP strategy is 15 minutes, and the delay to shelter for the PS strategy is 1 hour to allow sufficient time for the public to pack up, secure the home, and travel to the PS.

- It is assumed that evacuation begins 30 minutes following warning time.
- Sheltering periods of 2, 4, and 8 hours were considered, followed by either a radial or lateral evacuation.
- Distance from the plant to the site boundary is assumed to be 0.5 km (0.31 mi). Beyond the site boundary, a hypothetical 16-km (10-mile) EPZ was established with a uniform population density of 100 persons per km^2 (256 persons per mi^2). This population density corresponds to an EPZ population of 80,000. The assumed value of the population density does not affect the results since they are normalized. Simple scaling would allow the determination of number of consequences for different EPZ population densities; however, one must remember that this sample site is a uniform distribution which would not be representative of any existing NPP site.
- Evacuation time estimates evaluated include 4, 6, 8, and 10 hour ETEs. Travel speeds are calculated so that a person near the site boundary would reach the 16-km (10-mile) radius at the prescribed ETE. These values were selected to represent a common range of ETEs and were based on review of approximately 10 current ETEs and review of NUREG / CR-1856, "An Analysis of Evacuation Time Estimates Around 52 Nuclear Power Plant Sites" (NRC, 1981). It is not intended to imply that 4 hours is a minimum or 10 hours is a maximum evacuation time.

  - 4-hour ETE - travel speed = 1.08 m/s (2.5 mph)
  - 6-hour ETE - travel speed = 0.72 m/s (1.67 mph)
  - 8-hour ETE - travel speed = 0.54 m/s (1.25 mph)
  - 10-hour ETE - travel speed = 0.43 m/s (1.0 mph)

- MACCS2 allows a change in the travel speed of a cohort between radial distances from the plant. MACCS2 does not allow a percentage of a cohort to stay put while the remainder moves thus variable speed was used to approximate a staged evacuation. For the staged evacuation scenario, the evacuation speed was varied over three time intervals, such that the population would travel a little faster speed for the first 3.2 km (2 miles), slower for the next 4.8 km (3 miles), and even slower for the next 8 km (5 miles). The overall evacuation times remain the same. These variable speeds included:

  - 4-hour ETE - travel speed = 3.02/1.51/0.75 m/s (6.8/3.4/1.7 mph)
  - 6-hour ETE - travel speed = 2.01/1.01/0.50 m/s (4.5/2.3/1.1 mph)
  - 8-hour ETE - travel speed = 1.51/0.75/0.38 m/s (3.4/1.7/0.85 mph)
  - 10-hour ETE - travel speed = 1.21/0.60/0.30 m/s (2.7/1.3/0.67 mph)

- A total of four source terms were considered. As stated earlier, it is not the intent of this report to validate the magnitude or frequency of these source terms. The source terms are used to create the consequence analysis files for use in determining the relative ranking of alternative protective actions. Thus, a rapidly evolving source term and a progressively evolving source term were selected as described earlier. The source terms are described as follows:

  - Source Term 1 (ST-1): Interfacing System Loss of Coolant Source Term [Pressurized Water Reactor (PWR) Bypass]; 40 minutes from declaration of a General Emergency (GE) to release and 6-hour duration, and

- Source term 2 (ST-2): Fire with Containment Venting Source Term [Boiling Water Reactor (BWR) Fire]; 3 hours from declaration of a GE to release and 10-hour duration.

- To add depth to the analysis, two additional source terms were created. These are fictitious accident sequences that utilize the same source term values as ST-1 and ST-2, but the release timing has been modified such that:

  - ST-1M: 3 hours from declaration of a GE to release and 6-hour duration; and
  - ST-2M: 40 minutes from declaration of a GE to release and 10-hour duration.

  Other than the initial timing of the release, ST-1M is identical to ST-1 and ST-2M is identical to ST-2 in terms of magnitude of release, timing, and duration.

- The scheme chosen for meteorological sampling is the weather-binning option for MACCS2. Under this option, the hourly weather data are binned into a total of up to forty (40) bins that differentiate wind speed, atmospheric stability class, and precipitation rate. Thirty-six (36) bins were defined for this study and are identical to those in Sample Problem A described in the MACCS2 user's manual (NRC, 1998). The maximum of 5% of the samples or twelve (12) were selected from each bin. The weather data are from Moline, Illinois, which are the standard weather data used for NRC calculations when applied to a generic site. These choices resulted in a total of 543 weather trials to represent the 8,760 hours of data in a 365-day year. These weather trials account for the uncertainty in the weather at the time of a future, hypothetical accident.

  For the adverse weather (precipitation) scenario, only those precipitation events (rain or snow) that occur before the plume exits the 16-km (10-mile) EPZ are used in the analysis.

- Dispersion is calculated using the standard Tadmor and Gur (1969) lookup tables. This is identical to Sample Problem A. A scaling factor of 1.27 was used for vertical dispersion to represent a surface roughness of 10 cm, which is a number typically used for U.S. sites.
- The Briggs (1971, 1972) plume rise model is used to determine the plume rise under conditions where the plume is significantly more buoyant than the surrounding atmosphere.
- A single cohort is used to represent the population within the EPZ. This cohort represents the large majority, which NRC normally assumes to be 99.5%, that cooperate with the authorities and responds as instructed. This is consistent with Sample Problem A and ignores the segment of the population who refuse to evacuate or shelter when instructed to do so. The rationale for neglecting this group is that they would receive the same dose regardless of the emergency response strategy, and therefore, they do not help to distinguish the efficacy of the strategy.
- A set of protection factors are used to scale the exposures during evacuation (assumed to be in an automobile), normal activity (a combination of indoor and outdoor activities), and sheltering. Protection factors are specified for each of the pertinent pathways: cloudshine, groundshine, deposition onto the skin, and inhalation. The sheltering values (Table 5.1) vary with time to account for air exchange rates within the shelter structures.

Table 5.1 - Protection Factors used in MACCS2 Calculations

Activity		Cloudshine	Inhalation	Skin	Groundshine
Evacuation		1	0.98	0.98	0.5
Normal Activity		0.75	0.41	0.41	0.33
Shelter-in-Place	**2-hours**	0.6	0.46	0.46	0.2
	4-hours		0.66	0.66	
	8-hours		0.82	0.82	
Preferential Shelter	**2-hours**	0.31	0.21	0.21	0.02
	4-hours		0.37	0.37	
	8-hours		0.57	0.57	

The protection factors for preferential sheltering were calculated for a typical high school gymnasium constructed of concrete blocks and with a metal roof. For an initial, constant external contaminant concentration, C_0, the increase in internal contaminant concentration, C, with exposure time, t, is related to the air exchange rate per hour (ACH), shown in Equation 1.

$$C/C_0 = 1 - e^{-(ACH)t} \qquad \text{(Eq. 1)}$$

The time-averaged contaminant fraction infiltrating the preferential shelter was calculated for each shelter duration time using the integral of Eq. 1:

$$f(t) = 1 - [1 - e^{-(ACH)t}]/(ACH)t \qquad \text{(Eq. 2)}$$

Using Figure 5.2, where ACH=0.25 represents PS and ACH=0.7 represents SIP, the contaminant fractions were calculated using Eq. 2 to obtain the 2, 4, and 8-hour shelter protection factors for inhalation and skin dose (see Table 5.1).

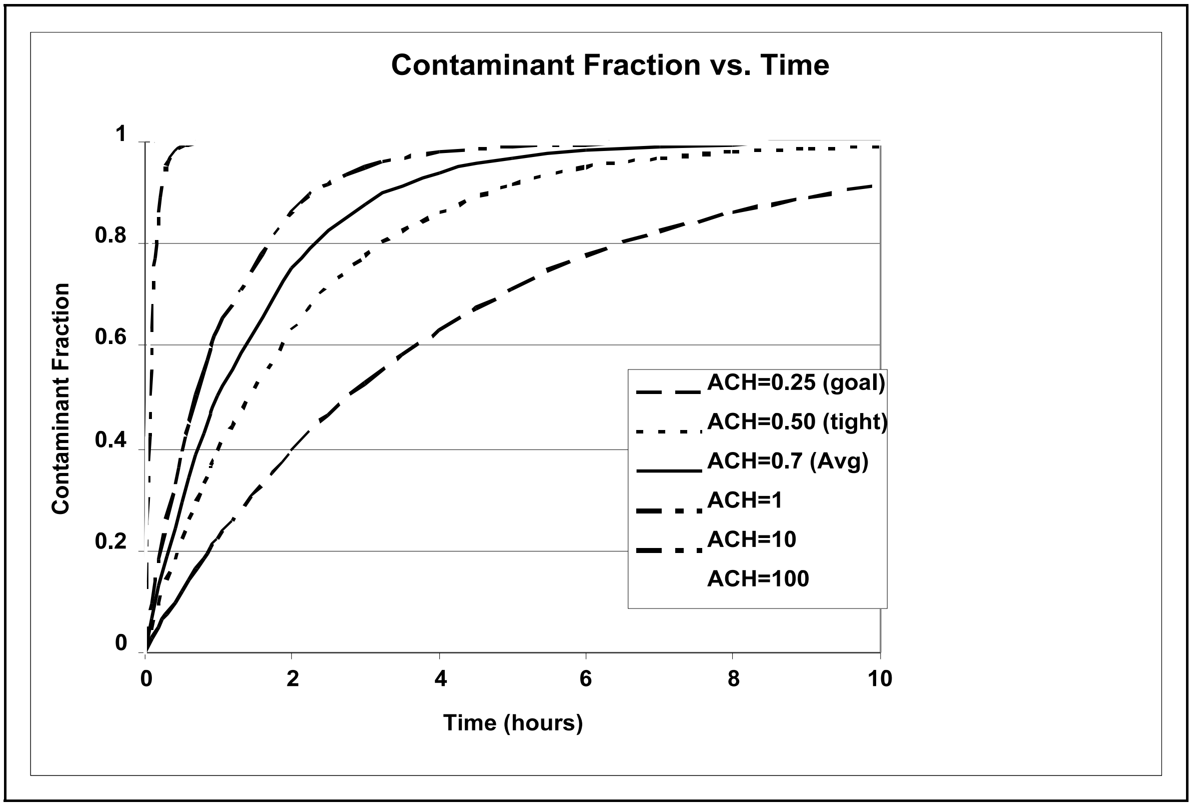

Figure 5.2 - Plot of Equation 1 for a wider range of ACH values, where ACH=0.25 represents PS and ACH=0.7 represents SIP.

5.3 Calculations

The following strategies were evaluated in the MACCS2 calculations:

- Immediate radial evacuation (Baseline);
- Shelter-in-place followed by radial evacuation;
- Shelter-in-place followed by lateral evacuation;
- Preferential sheltering followed by radial evacuation;
- Preferential sheltering followed by lateral evacuation; and
- Staged evacuation evaluated as a variable speed.

Each of the shelter strategies included calculations of 2, 4, and 8 hour shelter periods. As a result, 14 scenarios were actually assessed for each of the 4 ETEs. In addition, an adverse weather scenario was assessed as well as a no containment failure accident.

5.3.1 Immediate Radial Evacuation (Baseline)

The baseline protective action strategy is immediate radial evacuation where evacuees travel in a general radial direction away from the plant to exit the EPZ. The evacuation in a general radial direction is required in NUREG-0654 / FEMA-REP-1, Rev.1 (NRC, 1980). It is assumed that evacuation begins 30 minutes following the warning.

5.3.2 Shelter-in-place followed by Radial and Lateral Evacuation

SIP is defined as a protective action strategy where individuals remain in either their residence or the facility where they happen to be when the notification to SIP is announced. This strategy includes SIP for 2, 4, or 8 hour times followed by radial evacuation. There is a 15 minute delay from the warning until the population is assumed to be sheltered in place. Radial evacuation for 4, 6, 8, and 10 hour times are examined. Lateral evacuation is also examined for each shelter duration time as well as each evacuation time.

5.3.3 Preferential Sheltering followed by Radial and Lateral Evacuation

The PS strategy requires an individual to go to a designated center, which is located within the 16-km (10-mile) EPZ and provides greater shielding protection than a personal residence. Schools, government, and commercial buildings offer increased protection over a residence and may be only minutes away from the affected population, whereas evacuation travel time to a location outside of the 16-km (10-mile) EPZ could be significantly longer. To account for the need to pack, secure the home or business, gather the family, and travel to the PS, there is a 1 hour delay from the warning until the population is assumed to be sheltered. This strategy includes PS for 2, 4, or 8 hour times followed by radial evacuation. Radial and lateral evacuation times, of 4, 6, 8, and 10 hour times are examined.

5.3.4 Staged Evacuation

A staged evacuation is where one geographic area evacuates while other adjacent areas stay in place. Staged evacuations occur frequently in the United States and present a structured and efficient option to a keyhole evacuation. The purpose of staging an evacuation is to allow an area with the highest risk to be evacuated first with little effect from background traffic on the roadways. The traffic control is established to limit vehicles entering the roadway or passing through the area to facilitate movement of those that need to evacuate. Because the number of evacuees is limited to the select geographical area and traffic is controlled the evacuating public can move more quickly on the roadways.

The version of MACCS2 used in this analysis does not allow a part of a cohort group to remain in place while another part moves. Therefore, to best estimate a staged evacuation within MACCS2, a variable speed evacuation was modeled. This strategy allows evacuees that are nearer to the plant to evacuate at a faster speed than those farther away. In the staged evacuation scenario, the public would evacuate at one rate for the first 3.2 km (2 miles), a slightly slower rate for the next 4.8 km (3 miles), and an even slower rate for the next 8 km (5 miles); however, the average evacuation speed assumed for these calculations is equal to the rate required to produce 4, 6, 8, and 10 hour ETEs. This does not precisely evaluate a staged evacuation, but does simulate the effects of moving more quickly from the higher risk areas and these results can be used as being representative of a staged evacuation.

5.4 MACCS2 Results

Table 5.2 summarizes the source terms used in the consequence analyses. The results of the analyses are presented in Tables 5-3 through 5-6 which provide the relative benefit of the alternative protective actions as compared to the baseline radial evacuation. The full set of normalized results is presented in Appendix B. Each set of alternative protective actions was assessed for a 4, 6, 8, and 10 hour ETE. The results are ranked according to the benefit provided and includes consideration of early fatalities as well as latent cancer fatalities. In some instances, the difference in benefit from the alternative protective action and the baseline radial evacuation was not significantly different. These instances are noted where the occur.

Table 5.2 - Source Terms Considered

Conditions	40-minute to Release	3-hour to Release
Short Duration (6.6-hour)	ST-1	ST-1M
Long Duration (10.5-hour)	ST-2M	ST-2

5.4.1 Rapidly Progressing Accident

A rapidly progressing accident is highly unlikely, but is included in the emergency preparedness planning basis. In a rapidly progressing accident, the results in Tables 5.3 A-D, indicate that shelter strategies and staged evacuation result in a lower population dose and peak dose than the baseline radial evacuation for all ETEs evaluated. Both SIP and PS strategies provide a greater benefit than the baseline evacuation strategy. For the rapidly progressing accident, the baseline radial evacuation is the least beneficial for all ETEs evaluated. This analysis is supportive of a conclusion to revise NUREG-0654, Supplement 3 (NRC, 1996) to include more detail on the decision process for selecting a shelter based protective action.

Table 5.3A. Source Term ST-1, 4-hour ETE

Protective Action	Benefit
PS-2hrs/Lateral Evac	Significantly Improved Benefit
PS-4hrs/Lateral Evac	
PS-4hrs/Radial Evac	
PS-8hrs/Lateral Evac	
PS-2hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
SIP-2hrs/Lateral Evac	Improved Benefit
PS-8hrs/Radial Evac	
SIP-4hrs/Radial Evac	
SIP-8hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-2hrs/Radial Evac	
Staged Evac	
Radial Evacuation (constant speed)	**Baseline**

Table 5.3B. Source Term ST-1, 6-hour ETE

Protective Action	Benefit
PS-2hrs/Lateral Evac	Significantly Improved Benefit
PS-4hrs/Lateral Evac	
PS-4hrs/Radial Evac	
PS-2hrs/Radial Evac	
PS-8hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
PS-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	Improved Benefit
SIP-2hrs/Lateral Evac	
SIP-8hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
Staged Evac	
SIP-2hrs/Radial Evac	
Radial Evacuation (constant speed)	**Baseline**

Table 5.3C. Source Term ST-1, 8-hour ETE

Protective Action	Benefit
PS-2hrs/Lateral Evac	Significantly Improved Benefit
PS-4hrs/Lateral Evac	
PS-2hrs/Radial Evac	
PS-4hrs/Radial Evac	
PS-8hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
PS-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	Improved Benefit
SIP-2hrs/Lateral Evac	
SIP-8hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
SIP-2hrs/Radial Evac	
Staged Evac	
Radial Evacuation (constant speed)	**Baseline**

Table 5.3D. Source Term ST-1, 10-hour ETE

Protective Action	Benefit
PS-2hrs/Lateral Evac	Significantly Improved Benefit
PS-4hrs/Lateral Evac	
PS-4hrs/Radial Evac	
PS-2hrs/Radial Evac	
PS-8hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
PS-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	Improved Benefit
SIP-2hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-2hrs/Radial Evac	
Staged Evac	
Radial Evacuation (constant speed)	**Baseline**

5.4.2 Progressive Accident

For the more slowly progressing source term (ST-2), also a highly unlikely event, and the two modified source terms (ST-1M and ST-2M) the benefit from alternative protective actions is not as evident. For the 4 and 6 hour ETEs and source term ST-2 (Tables 5.4A and 5.4B), some alternative protective actions provide equal benefit to immediate radial evacuation but none of the alternatives provided greater protection. The longer shelter periods provide less benefit than radial evacuation. For the 8 and 10 hour ETEs, (Tables 5.4C and 5.4D), a short shelter period of 2 or 4 hours followed by lateral evacuation provides improved benefit over radial evacuation. However, this is only a benefit if the subsequent evacuation is lateral. Staged evacuation also provides improved benefit over radial evacuation for the 8 and 10 hour ETEs.

For source term ST-1M (Tables 5.5A through 5.5D) where there is a 3 hour warning time, SIP for 2 hours with subsequent lateral evacuation always provided the greatest benefit. Again, this is a benefit only if the evacuation is lateral. Immediate radial evacuation was most beneficial for the 4 hour ETE, but ranked lower for 6, 8 and 10 hour ETEs.

For source term ST-2M (Tables 5.6A through 5.5D), SIP for 2 hours with subsequent lateral evacuation always provided the greatest benefit. As with the other source terms, this is a benefit only if the evacuation is lateral. For all of the remaining ETEs, a short duration shelter followed by lateral evacuation also provided greater benefit than radial evacuation. Staged evacuation provided greater benefit than radial evacuation for these ETEs as well.

Table 5.4A. Source Term ST-2, 4-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	**Baseline** (not significantly different than Baseline)
PS-2hrs/Lateral Evac	
Staged Evac	
Radial Evacuation (constant speed)	
SIP-2hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
PS-4hrs/Lateral Evac	
PS-2hrs/Radial Evac	
SIP-4hrs/Radial Evac	Less Benefit
SIP-8hrs/Lateral Evac	
PS-4hrs/Radial Evac	
PS-8hrs/Lateral Evac	
SIP-8hrs/Radial Evac	Significantly Less Benefit
PS-8hrs/Radial Evac	

Table 5.4B. Source Term ST-2, 6-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	**Baseline** (not significantly different than Baseline)
PS-2hrs/Lateral Evac	
Staged Evac	
Radial Evacuation (constant speed)	
SIP-4hrs/Lateral Evac	
PS-4hrs/Lateral Evac	
SIP-2hrs/Radial Evac	Less Benefit
PS-2hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	
PS-4hrs/Radial Evac	
PS-8hrs/Lateral Evac	Significantly Less Benefit
SIP-8hrs/Radial Evac	
PS-8hrs/Radial Evac	

Table 5.4C. Source Term ST-2, 8-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	Improved Benefit
PS-2hrs/Lateral Evac	
SIP-4hrs/Lateral Evac	
PS-4hrs/Lateral Evac	
Staged Evac	
Radial Evacuation (constant speed)	**Baseline**
SIP-2hrs/Radial Evac	Less Benefit
PS-2hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	Significantly Less Benefit
PS-8hrs/Lateral Evac	
PS-4hrs/Radial Evac	
SIP-8hrs/Radial Evac	
PS-8hrs/Radial Evac	

Table 5.4D. Source Term ST-2, 10-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	Significantly Improved Benefit
PS-2hrs/Lateral Evac	
SIP-4hrs/Lateral Evac	
PS-4hrs/Lateral Evac	
Staged Evac	Improved Benefit
Radial Evacuation (constant speed)	**Baseline**
SIP-2hrs/Radial Evac	Less Benefit
SIP-8hrs/Lateral Evac	
PS-2hrs/Radial Evac	
PS-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	Significantly Less Benefit
PS-4hrs/Radial Evac	
SIP-8hrs/Radial Evac	
PS-8hrs/Radial Evac	

Table 5.5A. Source Term ST-1M, 4-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	**Baseline** (not significantly different than Baseline)
Staged Evac	
Radial Evacuation (constant speed)	
PS-2hrs/Lateral Evac	Less Benefit
PS-4hrs/Lateral Evac	
PS-8hrs/Lateral Evac	
PS-8hrs/Radial Evac	
PS-4hrs/Radial Evac	Significantly Less Benefit
SIP-2hrs/Radial Evac	
SIP-4hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-4hrs/Radial Evac	
PS-2hrs/Radial Evac	

Table 5.5B. Source Term ST-1M, 6-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	Significantly Improved
Staged Evac	Improved Benefit
PS-2hrs/Lateral Evac	
PS-4hrs/Lateral Evac	**Baseline**
Radial Evacuation (constant speed)	(not significantly different than Baseline)
PS-4hrs/Radial Evac	Less Benefit
PS-8hrs/Radial Evac	
PS-8hrs/Lateral Evac	
SIP-4hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-2hrs/Radial Evac	Significantly Less Benefit
SIP-4hrs/Radial Evac	
PS-2hrs/Radial Evac	

Table 5.5C. Source Term ST-1M, 8-hour ETE

Protective Action	Benefit
SIP-2hrs/Lateral Evac	Significantly Improved
PS-8hrs/Lateral Evac	Improved Benefit
PS-4hrs/Lateral Evac	
Staged Evac	
PS-2hrs/Lateral Evac	
PS-4hrs/Radial Evac	
PS-8hrs/Radial Evac	
SIP-8hrs/Lateral Evac	
SIP-8hrs/Radial Evac	
Radial Evacuation (constant speed)	**Baseline**
SIP-4hrs/Lateral Evac	Less Benefit
SIP-4hrs/Radial Evac	
PS-2hrs/Radial Evac	Significantly Less Benefit
SIP-2hrs/Radial Evac	

Table 5.5D. Source Term ST-1M, 10-hour ETE

Protective Action	Benefit
SIP-2 hrs/Lateral Evac	Significantly Improved Benefit
Staged Evacuation	
PS-4 hrs/Lateral Evac	
PS-8 hrs/Lateral Evac	Improved Benefit
PS-8 hrs/Radial Evac	
SIP-8 hrs/Lateral Evac	
PS-4 hrs/Radial Evac	
SIP-8 hrs/Radial Evac	
SIP-4 hrs/Lateral Evac	
PS-2 hrs/Lateral Evac	
Radial Evacuation (constant speed)	**Baseline**
SIP-4 hrs/Radial Evac	Less Benefit
SIP-2 hrs/Radial Evac	Significantly Less Benefit
PS-2 hrs/Radial Evac	

Table 5.6A. Source Term ST-2M, 4-hour ETE

Protective Action	Benefit
Staged Evacuation	**Baseline** (not significantly different than Baseline)
SIP-2 hrs/Lateral Evac	
PS-2 hrs/Lateral Evac	
Radial Evacuation (constant speed)	
PS-4 hrs/Lateral Evac	
SIP-4 hrs/Lateral Evac	
SIP-2 hrs/Radial Evac	Less Benefit
PS-2 hrs/Radial Evac	
SIP-4 hrs/Radial Evac	
PS-4 hrs/Radial Evac	
SIP-8 hrs/Lateral Evac	Significantly Less Benefit
PS-8 hrs/Lateral Evac	
PS-8 hrs/Radial Evac	
SIP-8 hrs/Radial Evac	

Table 5.6B. Source Term ST-2M, 6-hour ETE

Protective Action	Benefit
SIP-2 hrs/Lateral Evac	Improved Benefit
PS-2 hrs/Lateral Evac	
PS-4 hrs/Lateral Evac	
SIP-4 hrs/Lateral Evac	
Staged Evacuation	
Radial Evacuation (constant speed)	**Baseline**
SIP-2 hrs/Radial Evac	Less Benefit
PS-2 hrs/Radial Evac	
SIP-4 hrs/Radial Evac	
PS-4 hrs/Radial Evac	Significantly Less Benefit
SIP-8 hrs/Lateral Evac	
PS-8 hrs/Lateral Evac	
PS-8 hrs/Radial Evac	
SIP-8 hrs/Radial Evac	

Table 5.6C. Source Term ST-2M, 8-hour ETE

Protective Action	Benefit
SIP-2 hrs/Lateral Evac	Significantly Improved Benefit
PS-2 hrs/Lateral Evac	
SIP-4 hrs/Lateral Evac	Improved Benefit
PS-4 hrs/Lateral Evac	
Staged Evacuation	
Radial Evacuation (constant speed)	**Baseline**
SIP-2 hrs/Radial Evac	Less Benefit
PS-2 hrs/Radial Evac	
SIP-8 hrs/Lateral Evac	Significantly Less Benefit
PS-8 hrs/Lateral Evac	
SIP-4 hrs/Radial Evac	
PS-4 hrs/Radial Evac	
PS-8 hrs/Radial Evac	
SIP-8 hrs/Radial Evac	

Table 5.6D. Source Term ST-2M, 10-hour ETE

Protective Action	Benefit
SIP-2 hrs/Lateral Evac	Significantly Improved Benefit
PS-2 hrs/Lateral Evac	
SIP-4 hrs/Lateral Evac	
PS-4 hrs/Lateral Evac	Improved Benefit
Staged Evacuation	
Radial Evacuation (constant speed)	**Baseline**
SIP-2 hrs/Radial Evac	Less Benefit
PS-2 hrs/Radial Evac	
SIP-8 hrs/Lateral Evac	
PS-8 hrs/Lateral Evac	
SIP-4 hrs/Radial Evac	Significantly Less Benefit
PS-4 hrs/Radial Evac	
PS-8 hrs/Radial Evac	
SIP-8 hrs/Radial Evac	

5.4.3 No Containment Failure

Typical source terms associated with non-bypass no-containment failure (NCF) events at the Surry NPP were compared to source term ST-1, which is an ISLOCA source term. As stated previously, any accident is highly unlikely. This review included the highest probability NCF source terms of these unlikely events for all major initiating event classes, including events resulting in vessel breach, as well as those for which the vessel remained intact.

Although some differences could be seen between the NCF source terms, particularly between events resulting in vessel breach and those for which the vessel remained intact, the relative comparison between all of the NCF source terms and ST-1 remained the same. In general:

- On the order of 0.1% of the total noble gas (NG) core inventory is typically released during the Surry NCF source terms compared to essentially all of the NG inventory for ST-1;
- On the order of 0.001% of the total halogen (I) core inventory is typically released during the Surry NCF source terms compared to approximately 10% for ST-1;
- Releases of all other species are at least five orders of magnitude smaller for the Surry NCF source terms than ST-1; and
- The durations of the Surry NCF source terms are a factor of 10 longer than ST-1 and have a significant longer lead time between warning and release.

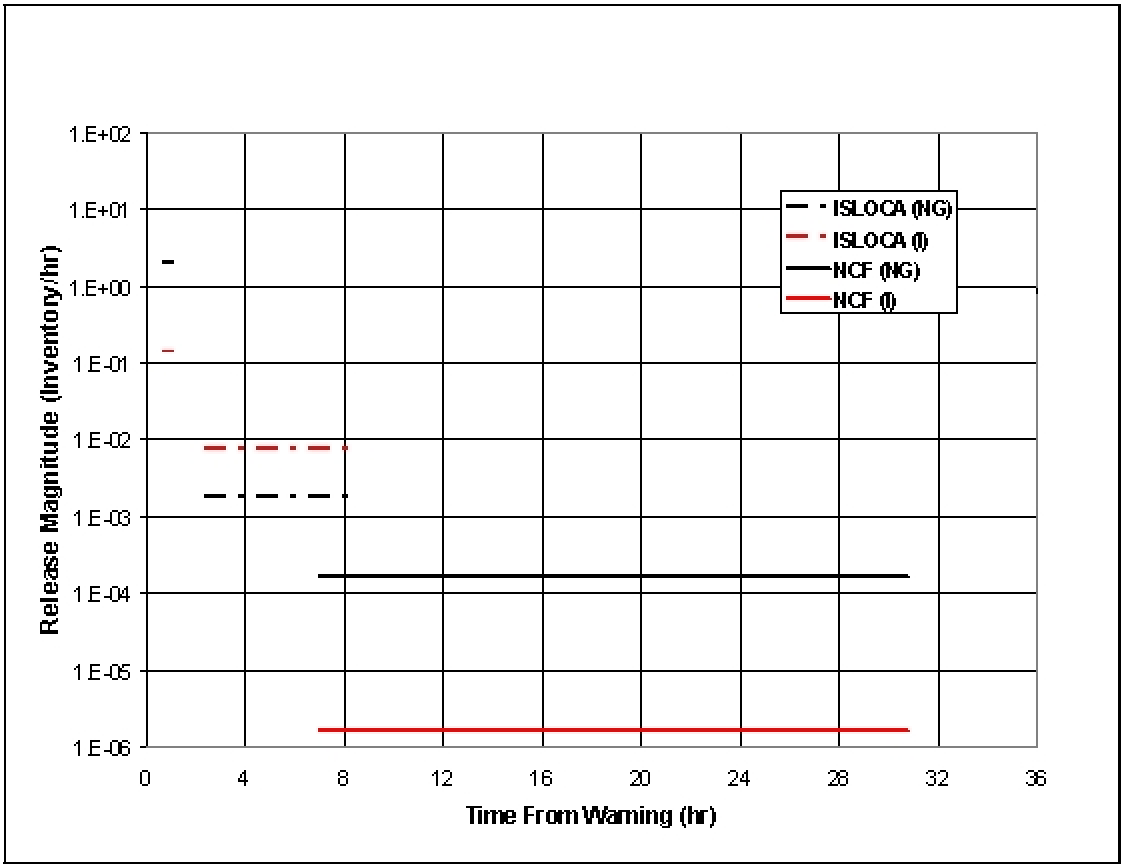

Figure 5.3 - Comparison of the noble gas (NG) and halogen (I) release rates and durations for a typical Surry non-bypass no containment failure (NCF) and ISLOCA. The NCF source term is typical of major internal and external initiating events resulting in vessel breach and no vessel breach.

MACCS2 calculations were conducted to evaluate the dose to the public for general emergencies where containment remains intact. The existing source terms and timings were used, and exposure was evaluated over a 24-hour time period. Based on a review of the literature, containment leakage rates of 0.1, 0.25, and 0.5% were examined (Table 5.7). The total effective dose equivalent (TEDE) and thyroid dose were examined for 5 downwind distances 0.8, 1.6, 3.2, 8 and 16-km (0.5, 1, 2, 5, and 10 miles).

Table 5.8 provides the number of hours until the evacuation threshold is exceeded. With the NCF source term, relatively low doses are received by the public. With a leakage rate of 0.1%/day, the dose at which evacuation would be required is exceeded:

- Within 8 hours at a 0.8-km (0.5-mile) radius of the plant; and
- Within 16 hours at a 1.6-km (1-mile) radius of the plant.

With a leakage rate of 0.5%/day, the dose at which evacuation would be required is exceeded the dose at which evacuation would be required is exceeded:

- Within 2.5 hours at a 0.8-km (0.5-mile) radius;
- Within 4 hours at a 1.6-km (1-mile) radius; and
- Within 8 hours at a 3.2-km (2-mile) radius of the plant.

Containment Type	Leakage Rate	Comments
Large Dry	0.1 volume %/day for 0-24 hrs, 0.05 volume %/day > 24 hrs	Comanche Peak FSAR
	0.1 volume %/day for 0-24 hrs, 0.045 volume % / day > 24 hrs	Indian Point FSAR
Subatmospheric	0 volume %/day	By Definition
Ice Condenser	0.25% of the containment free air volume per day at accident pressure of 12 psig	Sequoyah FSAR: Pressure of 12 psig
BWR MARK-I	0.5 volume %/day at 56 psig	Peach Bottom FSAR
BWR MARK-II	Unknown	See IPE/FSARS
BWR MARK-III	0.437 volume %/day at 11.4 psig (current FSAR reduces this to	Grand Gulf IPE: 0.385 volume % / Day
	0.65 volume %/day at 9 psig	Clinton (GGNS IPE)
	0.325 volume %/day at "the calculated peak containment pressure"	River Bend FSAR

Table 5.7 - Containment Leakage Rates for Various Types of Containment
Source: Individual Plant Examination (IPE) Reports and Final Safety Analysis Reports (FSAR).

Dose (rem)	Distance [km (mi)]	Leakage Rate (%/day)		
		0.10	**0.25**	**0.5**
TEDE	0.8 (0.5)	8	4	2.5
	1.6 (1.0)	16	7	4
	3.2 (2.0)	>24	15	8
	8.0 (5.0)	>24	>24	>24
	16.0 (10.0)	>24	>24	>24
Thyroid Dose	0.8 (0.5)	8	4	2.5
	1.6 (1.0)	16	6.5	4
	3.2 (2.0)	>24	14.5	8

Table 5.8 - Approximate Number of Hours until Evacuation Threshold is Exceeded

As the calculations indicate, off-site dose from an NCF accident can still exceed the threshold for evacuation from leakage through the containment. Table 5.8 shows that the evacuation threshold at the 3.2 km (2 mile) boundary would take 8 hours at a rate of 0.5% per day and longer for leakages of lesser magnitude. Because of the slow rates of leakage, the evacuation threshold at points farther from the plant take even longer and can be greater than 24 hours at the 16 km (10 mile) EPZ boundary. This provides additional time for the implementation of protective actions.

5.5 Other Considerations

This parametric study included testing of parameters to assess the potential effects on the alternative protective actions. In addition to the above calculations, an adverse weather condition was tested. The range of ETEs that were used were based on review of existing ETEs as well as NUREG / CR-1856 which is a comprehensive assessment of ETEs performed by the NRC in 1981 (NRC, 1981). Although this document is dated, review of existing ETEs indicates that the ranges of ETEs identified in NUREG / CR-1856 are still applicable.

5.5.1 Adverse Weather

The impact of adverse weather (precipitation) was assessed to determine how this would affect radionuclide transport and potentially impact the PAR options. Adverse weather was isolated from “average” weather by selecting only those weather sequences in which there was precipitation before the trailing edge of the initial plume moved beyond 12 km (the midpoint of the grid element extending from 8 km to 16 km) from the plant. Adverse weather, using this definition, comprises about 8.6% of the annual weather for Moline, Illinois. Favorable weather sequences are the set of the annual weather sequences in which no precipitation occurs before the trailing edge of the initial plume moves beyond 12 km from the plant. The intersection of these two sets of weather trials is null and the union forms the entire year of data, which represents the “average” weather.

The results of the adverse weather calculations revealed no demonstrable effect on the relative ranking of PAR options. The analysis indicates that precipitation tends to yield lower population dose and peak dose than the average weather scenario, assuming the ETE is held constant. Moisture may confer added benefits by enhancing radiation shielding directly, or by washing out radioactive particulates and gases and changing the dynamics of resuspension. Allowing for a 2 hour increase in evacuation time due to the adverse weather does not change this result.

5.5.2 Implications for Evacuation Time Estimate Studies

The results from this study show that selection of the most appropriate protective action is often dependent upon the evacuation time, and therefore, it is important to reduce the uncertainty associated with the ETE. When licensees prepare an ETE study, scenarios are developed to identify the combination of variables and events for normal and off-normal conditions to provide emergency planners with a realistic estimate of the time to evacuate under varying conditions. The ETE may be used by State and local authorities in making protective action decisions on whether to shelter or evacuate. The sequence of events for the ETE scenarios are usually include notification, preparation, and evacuation of the public. Although any nuclear power plant accident is unlikely, it may be beneficial to expand upon the ETE concept to address a potential accident with a rapidly progressive source term. The ETE could be calculated to include sheltering followed by evacuation in the sequence of events for the ETE scenario. The evacuation time may be different for a scenario that includes sheltering, because while individuals are sheltering, they would be preparing to evacuate. Upon receipt of instructions to evacuate, vehicles would immediately load the transportation network, as compared to a distributive loading that is currently assumed. Understanding any differences in evacuation time for scenarios where sheltering is recommended initially would help support the most appropriate protective action decision.

To assure the ETE is current when a protective action decision may be required, ETEs should be updated whenever changes occur that may affect the ETE, (NRC, 2005a) such as when EPZ populations are projected to increase or decrease, or when significant improvements are made to roadway and supporting infrastructure.

5.5.3 Modeling Uncertainty

The use of the MACCS2 model applied to a hypothetical site supports the qualitative approach conducted in this study. An extensive uncertainty analysis was not within the scope of this project, although uncertainty was addressed in some areas. MACCS2 is the NRC accepted model for calculating potential consequences, and the model was used in accordance with the guidance provided in the MACCS2 User's Manual (NRC, 1998). The objective of the project is to analyze the relative efficacy of a suite of alternative protective actions that may be implemented during a nuclear power plant emergency event. These events are low probability, and the protective actions considered are one element of a defense in depth program.

This project modeled a hypothetical reactor site including a range of source terms and a range of response parameters to produce consequence values. These values were then used to develop a qualitative ranking of alternative protective actions. Epistemic uncertainties within the modeling apply to all of the calculations. This project did not attempt to define the effect of any epistemic uncertainties, but recognizes that these uncertainties may exist. As stated frequently within this report, site specific analyses are necessary when developing protective action strategies.

In conducting the consequence modeling, aleatory uncertainty is accounted for through weather sampling. Sampling of the weather is essential because of the effect of stability class on the lateral extent of the plume and the potential for rain to wash out the plume contents over a population center. Some modeling values were varied parametrically including the magnitude of the source term, timing of the source term, evacuation times, evacuation speeds, sheltering durations, and shielding parameters. These parameters are the focus of the study and were varied to support the ranking of the alternative protective actions. Parameters that were not varied directly include the dispersion parameters and deposition velocities. It should be noted that while the dispersion parameters were not sampled directly, the magnitude of dispersion did vary over the weather trials since each trial uses its own set of hourly stability classes. While explicit sampling of dispersion parameters and deposition velocities was not performed, doing so would not have altered the relative ranking of the alternative protective actions.

The normalized values in Appendix A that were used to rank the alternative protective actions is applicable to the hypothetical site and supports a conclusion that alterative protective actions may be beneficial. When determining the most appropriate protective action, site specific data is needed, because there are site specific factors that may influence the protective action decision.

5.6 Summary of Consequence Modeling

Any core damage accident is highly unlikely and rapidly progressing accidents are even less likely, but are included in the emergency preparedness planning basis. The MACCS2 modeling was conducted for three accident conditions including:

- Rapidly progressing accident;
- Progressive accident; and
- No loss of containment accident.

5.6.1 Rapidly Progressing Accident

This modeling results indicate that in scenarios with a rapidly developing event of relatively high magnitude and short duration alternative protective action strategies are capable of reducing consequences. For ST-1, all of the alternative protective actions performed better than the baseline radial evacuation.

5.6.2 Progressive Accident

For releases of lesser magnitude and greater warning time, such as ST-1M, ST-2, and ST-2M, benefits from alternative protective actions would be more site specific because the benefits are frequently dependent on the ETE and the ability to conduct a lateral evacuation. The staged evacuation alternative resulted in fewer early and late consequences than the constant-speed evacuation scenario, indicating that it may be beneficial to take measures that will increase evacuation speed at early times. These measures might include staging the evacuation to allow certain at-risk populations to evacuate more quickly.

5.6.3 No Loss of Containment Accident

In an NCF accident, the leakage through the containment structure can be great enough to exceed the threshold for evacuation. The evacuation threshold at the 3.2 km (2 mile) boundary can be exceeded in 8 hours at a rate of 0.5% per day. Exceeding the evacuation threshold would take longer for leakages of lesser magnitude. Because of the slow rates of leakage, the evacuation threshold at points farther from the plant take even longer and can be greater than 24 hours at the 16 km (10 mile) EPZ boundary. This provides additional time for the implementation of protective actions.

5.6.4 General Conclusions from the Consequence Modeling

The following general conclusions have been developed based on the results of the consequence modeling:

- The results from the modeling show that PAR selection is dependent on the evacuation time, and therefore, it is important to reduce the uncertainty associated with the ETE. The ETE should be reevaluated whenever conditions change that may effect the ETE, such as a population increase or decrease, roadway improvements, or when alternative protective actions are integrated into the emergency planning.
- The modeling results indicate that there is a benefit to implementing alternative PAR strategies, including sheltering, lateral evacuation, and staged evacuation.
- The use of PS clearly results in fewer consequences for ST-1. However, the benefits are not as evident for all other source terms. For source terms ST-1M, ST-2 and ST-2M, PS is not typically more beneficial than the baseline evacuation. This lack of a significant benefit from PS should be factored into the consideration of a protective action that requires the level of infrastructure and support that PS would require.
- Although the modeling demonstrates that PS is not a significant benefit to the general public, sheltering of special needs individuals is similar in concept. In this case, most of the infrastructure necessary for PS is in place. When considering special needs facilities, the results indicate that it can be beneficial to shelter special needs individuals in their existing facilities. Sheltering not only provides time for these individuals to be prepared for evacuation, but also offers the time for emergency response teams to better assess the accident conditions which may affect whether there is any need to evacuate the special facilities.
- The modeling of shelter-in-place for the general public can also be viewed as delaying the evacuation. In this context, it is found that sheltering for short periods may be beneficial in allowing the local emergency responders to establish traffic control to facilitate an evacuation. This may have an added effect of reducing the evacuation time because traffic control can be fully established prior to the start of the evacuation.

6.0 ANALYSIS OF PROTECTIVE ACTION IMPLEMENTATION ISSUES

6.1 Alternative Protective Action Strategies

The consequence analysis identified that use of alternative protective actions can reduce consequences for some incidents. These alternative protective actions have been reviewed herein to assess potential issues related to implementation. In general, alternative protective actions should be limited to a few effective options because decision makers may not have sufficient time and / or information to sort through several different and potentially complex protective action strategies (EPA, 1991). Key considerations in deciding upon the appropriate PAR include the expected duration of the release and the anticipated dose to the public. There may be a high degree of uncertainty surrounding this information, including the precise magnitude and release timing of the source term, complexity of the terrain, or adverse weather conditions, all of which may make it difficult to accurately predict the plume (NRC, 1990a). Detailed consequence calculations and analysis were performed to identify and rank alternative protective actions that offer potential benefits. The following seven strategies were evaluated in the MACCS2 calculations:

- Radial evacuation;
- Lateral evacuation;
- Staged evacuation;
- Shelter-in-place followed by radial evacuation;
- Shelter-in-place followed by lateral evacuation;
- Preferential sheltering followed by radial evacuation; and
- Preferential sheltering followed by lateral evacuation.

6.1.1 Radial Evacuation

The baseline protective action assessed in this study is radial evacuation. Radial evacuation is the movement of people outward, away from the plant toward the EPZ boundary which is about 16 km (about 10 miles) away from the plant. Evacuation plans that generally direct the population radially are in place for all EPZs.

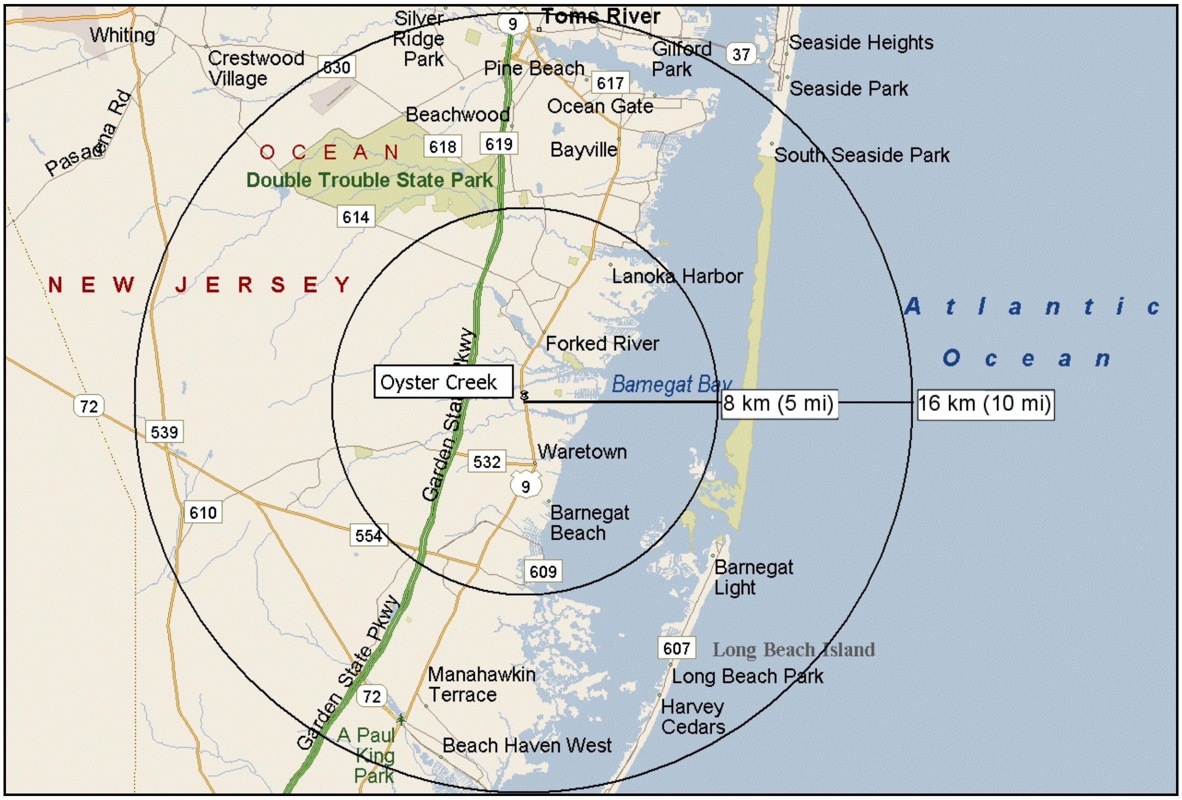

Figure 6.1 - Approximation of the emergency planning zone for a nuclear power plant showing radial roadway networks.

According to NUREG-0654 / FEMA-REP-1, Rev. 1 (NRC, 1980), evacuation should be based on general radial dispersion. This approach ensures that the evacuating public is getting further from the NPP regardless of the wind direction. There is a combination of lateral and radial movement that ultimately exits the EPZ. The EPZ in Figure 6.1 provides a good example of radial evacuation routing for wind directions to the north or south. Route 9 and the Garden State Parkway both run generally north / south through the EPZ providing the primary evacuation routes out of the EPZ.

6.1.2 Lateral Evacuation

The consequence assessment calculations indicate that lateral evacuation is capable of reducing consequences for all scenarios examined. Lateral evacuations move people perpendicular to the plume and out of the potential plume exposure area along the most direct route, which may also be a shorter distance. Implementation of lateral evacuation requires input from the meteorologists that are part of the response team. For instance, during the 24 hours following the Three Mile Island accident, the wind direction blew in virtually every sector of the EPZ. To support the assessment of lateral evacuations for this project, a review of meteorological data for approximately 10 sites was conducted, and all of these sites experienced changes in wind direction over the course of a 24 hour period. The meteorologists that support the incident response teams monitor local and regional conditions during an incident to anticipate these wind changes as they approach the vicinity of the EPZ. All EPZs receive meteorological data from at least one tower, and at some sites, such as those in Illinois, permanent radiological monitoring stations are located around each plant. These stations could also be bused to assist in determining the direction of a plume. The above information would support a protective action decision on the implementation of lateral evacuation.

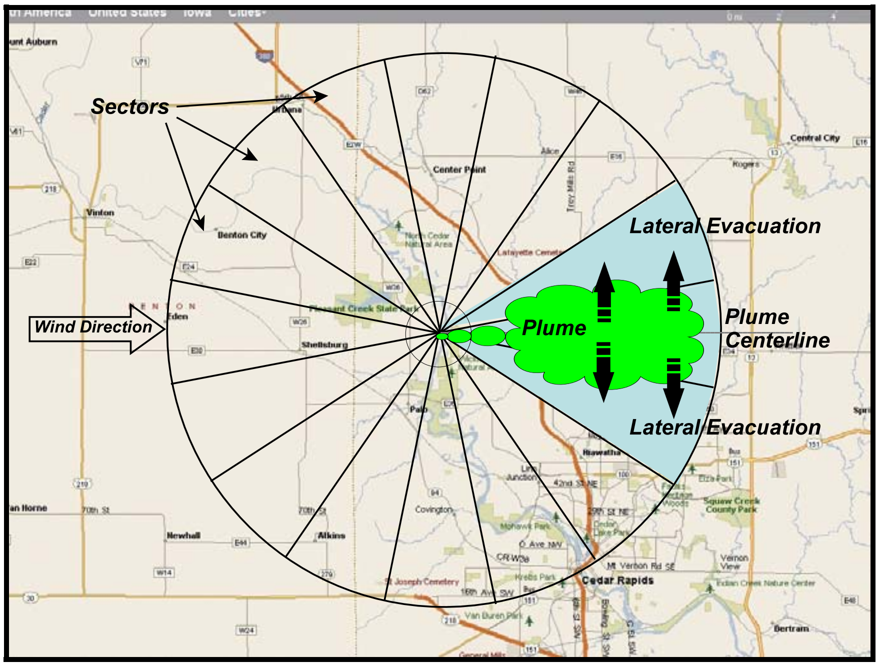

Figure 6.2. Lateral Evacuation Example.

In the EPZ shown in Figure 6.2, an Interstate crosses laterally through the sectors to be evacuated. Using the Interstate for this scenario results in a lateral evacuation. It may not be possible to implement the lateral evacuation strategy at all sites if the infrastructure does not support such an action. Discussion with stakeholders and review of mapping for all sites has confirmed that geography and configuration of the existing road network may physically constrain the direction that the public can evacuate. In a review of roadway networks for all EPZs, it appears that the infrastructure supports lateral evacuation in approximately 75% of the EPZs.

Lateral evacuation provides a reduction in consequences when it is implemented effectively. External factors, such as wind direction and variability as well as roadway infrastructure, may limit consideration of this protective action.

6.1.3 Staged Evacuation

In each consequence analysis evaluated, staged evacuation resulted in fewer consequences than standard radial evacuation. However, staged evacuation can be difficult to implement in a large scale evacuation. In some instances implementation issues may be mitigated with appropriate planning and effective traffic control. Limitations in the MACCS2 model require that a staged evacuation be modeled as a variable speed evacuation. Three speeds were assigned to simulate faster movement of the population early in the incident and slower movement as the roads become more congested. This modeling included moving people that live close to the hazard away from the hazard faster.

Preplanning is needed to support a staged evacuation approach and should consider the priorities for evacuating each of the affected areas of the EPZ. To implement a staged evacuation, select population groups would be evacuated prior to other population groups. This protective action is currently included in emergency plans in many States where early evacuation of schools and special facilities is planned at Site Area Emergency or earlier. Expanding this notification to larger population groups such as large industries within the EPZ that may require additional time to shut operations and possibly the 0-3.2 km (0-2 mile) zone. This would move people nearest the hazard first and also provide more time for facilities that may need this time to shut down operations.

Staged evacuation reduces on-road traffic demand and facilitates a more rapid evacuation of the high risk areas. However, the total evacuation time is typically unchanged since the same number of vehicles ultimately evacuate on the same roadway network. Staged evacuations are common and have been successfully implemented in natural disasters and technological hazards. Chen (2003) examined evacuation strategies and traffic networks in small-scale evacuation simulations and drew the following conclusions:

- The staged evacuation strategy works better on ring type roadway networks than on gridded networks;
- The staged evacuation strategy does not help reduce the total evacuation time significantly; and
- The performance of the staged evacuation strategy is highly dependent on the road network structure and the population density in the area of interest.

With a staged evacuation, the potential for a shadow evacuation of the surrounding areas exists. This must be addressed through communication with those residents in areas that are not designated to evacuate, combined with traffic control that facilitates the evacuation of the staged areas. When the staged areas in the EPZ begin evacuating, it may be necessary to control the shadow evacuation. The process to control the evacuation of the public that is outside the designated evacuation area begins with public education and awareness and may be managed during the incident through communication with the public and traffic control. Clear and direct communication stating that there is no need to evacuate may be provided to those individuals outside of the evacuation area. Communication methods could be used to inform the public that failure to follow instructions may affect the health and safety of those who need to evacuate.

Staged evacuations have been performed successfully for large scale natural disasters and have also been conducted for technological hazards. The 1979 evacuation of 218,000 people from Mississauga, Ontario is a well documented staged evacuation that is considered by experts to have been very successful. The Superior, Wisconsin train derailment in 1992 was a successful staged evacuation that included over 40,000 people from the cities of Superior, Wisconsin, Duluth, Minnesota, and surrounding areas (NRC, 2005b).

Another form of staged evacuation is the delay in evacuation of special needs groups. Delaying the evacuation of special needs groups can be beneficial for some special population groups such as those who are not readily mobile or have fragile health conditions. At least one State considers sheltering these populations for projected doses up to 5 REM and even 10 REM under some conditions. Depending on the type of special facility and condition of the individuals, delayed evacuation may be the most appropriate protective action.

6.1.4 Shelter-in-Place

SIP is a low-cost protective action that can provide protection with an efficiency ranging from zero to almost 100 percent (EPA, 1991). SIP is preferable when events develop rapidly and / or evacuation would be problematic (e.g., if the road network has been disrupted). In general, sheltering is preferred over evacuation whenever it provides equal or greater protection (EPA, 1991). In some instances, SIP may be the only protective action necessary. SIP is commonly implemented effectively for chemical hazards. There are a number of reasons to consider sheltering including; 1) there may be factors that affect an evacuation such as adverse weather; 2) there may be special needs facilities with individuals that may be very frail and difficult to evacuate; and 3) the plume may be traveling over the area faster than it is believed the public could evacuate. This is not an inclusive list and there may be other reasons for considering shelter.

Shelter-in-place is the most basic of protective actions and has been successfully implemented in *ad hoc* and preplanned events. Many local emergency planning committees throughout the country have developed brochures, videos, websites, and other educational tools to increase the awareness of this protective action in potentially affected areas. SIP is referenced in many State radiological emergency planning brochures as another way of reducing dose during certain radiological events. During an event, instructions for SIP, which are relatively brief (i.e., stay at your location, turn off the ventilation, seal doors and windows, etc.) can be readily conveyed through radio or television broadcast.

Successful implementation of a shelter protective action, for a severe accident, must include a means of ending the shelter event by notifying the public when to evacuate. The timing of the shelter termination is important to ensure the lowest dose to the public. The length of time that a shelter will continue to provide protection depends in part on the air infiltration rate, or ACH, for the facility (CSEPP, 2001). As the plume passes over the shelters, contamination penetrates into the shelter. The amount of contamination that enters the shelter is relative to the tightness of the shelter. Most shelters will allow some contamination inside; thus, once the plume has passed, it is important to leave the facility.

In a severe accident, the benefits from shelter diminish quickly if the notification to leave and subsequent evacuation are not conducted optimally. Analysis of some accidents show that sheltering in residences and buildings can be highly effective at reducing dose, although reliance on large dose reduction factors for sheltering should be accompanied by cautious examination of the local housing conditions (EPA, 1991). Implementation factors that affect the performance of the shelter include wind speed and temperature differentials. There is a fairly linear relationship to the outside wind speed and the air infiltration into the building. A house with an air exchange rate of 0.5 ACH in a calm period will have an estimated air exchange rate of 1 ACH at a wind speed of 6.43 km (4 mph) and 2 ACH at a wind speed of 12.87 km (8 mph) (ORNL, 2002). Temperature differences outside and inside the building also affect infiltration rates with the greater the temperature differential, the greater the infiltration. This is a necessary assessment when considering sheltering decisions in cold climate areas.

There are many case studies where SIP was successfully implemented, even with little or no public training or awareness. Some of these examples are identified in “Sheltering in Place as a Protective Action” (NICS, 2001) which includes events such as in Pittsburgh, California in 1998, when a refinery accident released 900 pounds of chlorine gas. Approximately 7,000 people in the surrounding community were alerted to SIP and did so successfully. On February 7, 1993, SIP was successfully implemented for 3 hours when a pipe fitting failed and released bromine gas in Ludington, Michigan. On July 26, 1993, a tank car carrying oleum ruptured in Richmond, California, sending a cloud of sulfur trioxide into the air, and employees of a nearby plant, sheltered in place and were not injured. In a final example, in Nitro, West Virginia on December 5, 1995, a chemical plant released a cloud of hydrochloric acid, and more than 800 employees of a neighboring chemical plant and several nearby offices successfully sheltered in place while the plume passed. In this last example, businesses in the area had been trained on sheltering. Although there was little or no training in the other cases, the public successfully sheltered in place because the message from the authorities was clear and concise and the consequences of not sheltering were clearly conveyed.

In a review of technical documentation on shelter-in-place, Environmental Protection Agency (EPA) 520 Parts I and II, “The Effectiveness of Sheltering as Protective Actions against Nuclear Accidents Involving Gaseous Releases” (EPA, 1978a and 1978b) examines sheltering as a protective action considering small structures and large structures to determine a dose reduction factor for various conditions. The study includes physical features, together with access-timing characteristics, to define the extent of protection that may be realized. The age and type of structures used for sheltering greatly affect the ACH. The Department of Energy study on the “Effectiveness of Sheltering in Buildings and Vehicles for Plutonium” (DOE, 1990) presents findings consistent with other studies stating that the airborne concentration within a shelter relative to that outside concentration depends primarily upon the rate at which air is exchanged with the outdoors, removal of the contaminant as it passes between the shelter and the outdoors, and the deposition rate of the contaminant within the shelter. Mobile home parks or other neighborhoods where there is housing that can not be easily sealed would not be good candidate areas for SIP.

The advantages of SIP include fairly quick implementation, no initial travel is required, it is effective at reducing the peak dose, and it is effective at reducing the cumulative exposure for a limited duration. The disadvantages are that the benefit from SIP diminishes with time, the population may still need to be evacuated and may receive a radiation dose from groundshine and the resuspension of contaminants during the subsequent evacuation if a release had occurred. Furthermore, there is a need for shelters to be assessed to assure they provide at least minimal protection. For example, mobile home parks may not provide sufficient shielding and may not be sealed well.

6.1.5 Preferential Shelter

Although the protection afforded by PS can be significant in certain scenarios, there are many implementation issues. For this strategy, individuals would be directed to designated buildings located within the 16-km (10-mile) EPZ that affords greater protection than their personal residence or workplace. Schools as well as large public and commercial buildings within the EPZ can offer significantly greater protection than normal housing and may be only minutes away from the affected population, whereas evacuation travel time to a location outside the 16-km (10-mile) EPZ could be significantly longer.

Development of a PS strategy at the EPZ level requires a much more coordinated effort and significantly more preplanning, including consideration of shelter ownership, responsible parties for ensuring shelter access and readiness, and information on population areas reporting to each shelter. Specific considerations for the PS strategy include:

- Location and number of shelters;
- Availability of shelters 24 hours per day, 7 days a week;
- Effectiveness of shelters;
- Capacity of shelters;
- Communications;
- Ventilation;
- Restroom facilities;
- Transport and access to shelters;
- Sufficient parking capacity at shelters;
- Security within the shelters;
- Termination plan for sheltering;
- Mobilization time to leave the shelters; and
- Transportation analysis.

Implementation of a PS strategy would require shelters to be located within the EPZ and should be no more than a few minutes drive for the affected population. These shelters would need to provide sufficient capacity for the expected population and be designed such that the total number at any given structure is not too large (i.e., approximately 1,000 people per shelter). This may drive the need for a large number of PS facilities within medium and high population density EPZs. Transportation to the shelters should be addressed to prevent traffic issues that may increase travel times to the shelter.

Establishing a preferential shelter program requires selecting, improving, and maintaining preferred shelter facilities. Although this is a very challenging commitment, it is not unprecedented. Large-scale shelter programs are implemented in response to natural disasters such as tornadoes and hurricanes as well as within the chemical stockpile emergency preparedness program. The CSEPP was established to ensure protection of public health and safety in the vicinities of the nation’s chemical stockpiles. The emergency planning in these vicinities is understandably very comprehensive and includes sheltering in specially designed facilities.

States such as New Jersey, North Carolina, Florida, and Illinois typically use schools for large shelters during natural disasters. A primary difference in use of shelters for hurricanes is the time available to activate the shelter for the public. A more comparable assessment may be the time to open shelters used in tornado zones where community shelter criteria specifies that all potential users of the shelter should be able to reach it within 5 minutes and the shelter doors should be secured within 10 minutes of the warning notice (FEMA, 2000). For a successful PS strategy, arrangements must be in place to open the facilities during non-standard hours and to ensure availability. A program would need to be established to assure that facility managers are available and accessible 24 hours a day to arrive at the shelter and open the facility. If the shelter is not open and accessible to the public when needed, the public is likely to evacuate, and the protection benefits calculated during emergency planning would not be achieved. With the large number of shelters that would be needed, it would be extremely difficult to ensure the availability of all of the shelters.

Shelter instructions include shutting off the heating, ventilation, and air-conditioning and sealing the doors, windows, and other openings to minimize air infiltration. These requirements are not necessary for tornado or hurricane shelter events where there is no contamination. To achieve the desired protection, selected facilities must have a means of shutting off the heating and air conditioning. However, because there will be a large number of people sheltering, some ventilation is necessary. Guidance for tornado shelters specifies a minimum ventilation rate of 0.14 m^3/min [5 ft^3/min (cfm)] per person (CSEPP, 1996). A PS plan would need to include some level of ventilation. This of course will allow infiltration of contaminates into the building and will reduce the effectiveness of the PS strategy. The ventilation requirement effectively eliminates the PS strategy from serious consideration as an alternative protective action. The infrastructure requirements for a large population EPZ would be very considerable and the ongoing maintenance of such a program would be very difficult to implement with confidence. The necessity of assuring availability during normal and off normal times as well as the ventilation of the shelters to accommodate large populations effectively eliminates the PS strategy from serious consideration as an alternative protective action.

6.1.6 Stakeholder Interaction

In assessing the practical issues of implementation, discussions with stakeholders were included beginning early planning activities and continued throughout the project. Detailed implementation aspects of the alternative protective actions discussed with respect to how off-site response organizations would actually implement potential alternative protective actions. The States of Virginia, New Jersey, and Illinois volunteered to support the NRC in discussions on this project. Members of cognizant agencies participated in meetings and conference calls to discuss the project approach and potential alternatives considered. These agencies included emergency management, health and safety, radiological agencies as well as first response organizations such as the State Police departments. The information gained from this participation provided valuable input into the assessment of the alternative protective actions. Some of this input is provided below:

- Once people get into their vehicle, they are more likely to evacuate rather than go to the PS;

- The time required to notify the PS facility manager and the potential need for that individual to enter the EPZ to open the facility presents an unrealistic expectation;
- Adequate facilities are not available in all sectors of each EPZ; and
- The time needed to gather enough data to make a confident decision that the plume has passed may be lengthy and difficult to determine precisely.

6.2 Assessment of Alternative Protective Action Burden

A qualitative estimate of regulatory burden for the assessed alternative protective actions is provided below with radial evacuation considered as the baseline protective action. For a severe accident the cost of closing businesses, travel out of the EPZ, temporary lodging, and lost revenues, etc., associated with evacuation are assumed to be equal for any protective action that is implemented. Table 6.1 provides a comparison of the regulatory burden elements compared to the baseline for each of the protective actions assessed. For the shelter strategies, it is assumed an evacuation would occur after the shelter.

Table 6.1 - Comparison of regulatory burden elements for protective action strategies.

Selected Regulatory Burden Elements	Radial Evacuation	Lateral Evacuation	Staged Evacuation	Shelter-in-Place	Preferential Shelter
Evacuation Planning	Baseline	Slightly Higher	Slightly Higher	Same	Higher
Communications	Baseline	Same	Same	Same	Higher
Traffic Control	Baseline	Slightly Higher	Slightly Higher	Same	Higher
Security	Baseline	Same	Same	Same	Higher
Infrastructure	Baseline	Same	Same	Same	Much Higher

To provide a baseline for comparison, it is assumed that no new infrastructure is necessary for the baseline radial evacuation. Additional regulatory burden elements to be considered for a lateral evacuation and staged evacuation include planning and traffic control. Lateral evacuation plans and updated traffic control plans would be need to be developed. An assessment would be needed to determine if additional resources and communications are necessary to monitor the meteorology and support the lateral evacuation. The planning burden is relatively minor and it is expected that additional resources would not be significant for other activities. SIP is for all practical purposes equivalent in regulatory burden to radial evacuation.

The regulatory burden to implement a PS protective action is high and will be site specific depending on the number and types of facilities within the EPZ that meet the performance criteria for PS. In coastal areas where hurricane shelters are pre-established, the additional cost may not be substantial. It is expected that the PS would be considered only at medium and large population sites where the ETEs are longer in duration and the public can not evacuate in a timely fashion. The extent of available facilities within an EPZ must be evaluated and determinations made on the potential use of these facilities for the PS protective action. Furthermore, the need to establish a program that ensures these facilities are available and maintained must also be included as a long term cost element. There are also additional traffic control and security requirements to manage the public at the shelters and there would be a need to establish reliable communications with each facility.

In this qualitative assessment, the only conclusions that can be readily stated are that for all but the PS strategy, regulatory burden is not a deciding factor. For the PS strategy, the regulatory burden of additional infrastructure and maintenance are higher than all other protective action strategies. An additional conclusion is that the risk of implementing the PS strategy is high because PS would be very difficult to implement with any assurance that the facilities would be available when needed.

6.3 Summary of Protective Action Implementation Issues

A summary of the implementation, realism, and regulatory burden advantages and disadvantages for alternative PARs is provided in Table 6.2. The site specific and accident specific characteristics must be considered in the determination of the appropriate protective action. For this reason, NRC guidance documents provide flexibility in establishing the most appropriate protective action recommendation. The alternative protective actions assessed for implementation show that these alternatives can be implemented under certain conditions; however, it is clear that the PS strategy would be impractical due to the need for potentially hundreds of facilities with 24 hour operational availability and ventilated facilities to shelter large population groups. The initial and ongoing infrastructure and program implementation regulatory burden for PS are very high demonstrating that there is no need for further consideration as an alternative protective action.

Radial evacuation is a proven protective action, and radial evacuations are implemented frequently in the U.S. There is room for improvement in identifying transport dependent and special needs individuals to better assure a complete evacuation. Lateral evacuation is capable of reducing consequences for the scenarios examined. Implementation of lateral evacuation requires moving the population perpendicular to the plume and this requires some confidence in the wind direction. Confidence in wind direction may be increased at sites where there are prevailing winds. If a wind shift does occur, emergency management may need to redirect the evacuating traffic and also may need to evacuate the newly affected sectors. Many sites can facilitate some level of lateral evacuation through the existing layout of the transportation infrastructure. Lateral evacuation requires minimal additional regulatory burden can provide an effective alternative protective when used appropriately.

Staged evacuation is one of the alterative protective actions that appears to be flexible in implementation and feasible in all EPZs. Some sites already implement staged evacuation by evacuating the schools, special facilities, beaches, and parks at Site Area Emergency or earlier. This appeared to be a trend at sites in roundtable discussions at the NRC sponsored Public Meeting on the Review of Emergency Preparedness Regulations and Guidance for Commercial Nuclear Power Plants, August 31 - September 1, 2005. Broadening early staged evacuations to the 0-3.2 km (0-2 mile) zone would support the movement of the population nearest the hazard first.

The use of SIP provides a reduction in consequences for some of the scenarios analyzed. The full benefit of the SIP strategy is only realized if followed by a lateral evacuation immediately after plume passage which exits the public from the contamination area in the most expedient manner. As this assessment demonstrates, in some EPZs lateral evacuation is inherent in the planning, whereas in other EPZs it cannot be effectively implemented. Recognizing the benefits of sheltering diminish if the subsequent evacuation is not optimized.

Table 6.2 Summary of advantages and disadvantages of PARs

Protective Action	Advantages	Disadvantages	Regulatory Burden
Radial Evacuation	Routes already posted. Can utilize ITS to improve. Routinely implemented in U.S. Public understands evacuation.	Length of time required to evacuate can be lengthy. Exposure during plume passage.	No additional regulatory burden (Baseline).
Lateral Evacuation	Moves population out of plume path the fastest. Can utilize ITS to improve. Travel distances are shorter.	Wind shift may require change in traffic direction. Requires accurate tracking of plume. Requires dual evacuation planning. Loss of public confidence if there is a wind shift requiring change of direction. Differs from posted evacuation route. Need ability to change direction if wind shifts.	Minor additional regulatory burden over Radial Evacuation.
Staged Evacuation	Moves the high risk population groups first. Can be applied early prior to General Emergency.	Requires minor additional resources to support staging. Public acceptance may be low.	Minor additional regulatory burden over Radial Evacuation.
Preferential Shelter	Provides greatest protection in some scenarios. Demonstrated application in CSEPP planning. Speed of implementation is faster than evacuation. Large scale sheltering has been implemented in hurricane and tornado areas.	Must mobilize to get to shelter. Requires many shelters. Requires shelter management program. Benefit diminishes if shelter termination is not optimal. Requires accurate tracking of plume. Once in vehicle, public may just evacuate. Public anxiety in a shelter may be high.	Requires ventilated facilities. Sustained high regulatory burden. Shelter program management burden. Security for each shelter. Traffic control for each shelter. Communications for each shelter.
Shelter-in-Place	Minimal action required by the public. Frequently implemented for technological hazards. Speed of implementation is high. Message easily conveyed. No initial travel required.	Benefit diminishes if shelter termination is not optimal. Requires accurate tracking of plume. Protective benefit may not be achieved if structure is inadequate. Public anxiety may be high.	Minor additional regulatory burden over Radial Evacuation to support subsequent lateral evacuation.

7.0 EFFICACY OF PAR STRATEGIES IN TERMS OF BEHAVIORAL AND SOCIOLOGY ISSUES

7.1 Introduction

The efficacy of alternative protective actions may be affected by the response of the public to these actions. If the affected population does not fully understand and respond appropriately to the protective measures, technically sound plans can be less effective than desired. If people do not believe that undertaking prescribed protective actions will make them more safe, or if they do not view protective action messages as credible, they may not respond as expected which may affect the overall success of the protective action. This section includes an evaluation of existing literature to assess the efficacy of alternative protective actions in terms of behavioral psychology and sociology. A more detailed and quantitative assessment of expected public behavior is provided in Volume II of this document.

The results of the consequence analyses showed that for rapidly developing events of relatively high magnitude and short duration, sheltering strategies and staged evacuation are capable of reducing early and latent fatalities. An evaluation of documented behavioral psychology and sociology issues that may affect the implementation of protective actions was completed for the alternative protective actions evaluated in this study.

7.2 Human Behavior During Emergencies

Social scientists such as Mileti (2000, 1990, 1984, 1992), Quarantelli (1985, 1992a,b, 1980), Tierney (2001, 2005), Dynes (1973), Drabek (1986, 2001, 1976, 1996, 1994, 1968, 1969, 1999), Fischer (1995, 1998a,b), and others have studied human behavior and response to disasters and emergencies for decades. Fundamental thinking regarding the human response to disaster has changed very little in the last forty years. Fischer (1998a,b) documented observed human behavior in the face of disaster and noted that:

- Emergency workers usually respond in an unselfish manner, putting the needs of the community above their personal needs;
- Emergency workers do not usually leave their posts to check on family members;
- Local leaders do not normally panic;
- People do not normally panic during a disaster;
- People help one another during a disaster; and
- People do not behave irrationally due to shock of the disaster.

Public behavior is influenced by the perception of risk, which is an important consideration for the success of any protective action recommendation. In a study of evacuation procedures for Hurricane Bret, Zhang, *et al.* (2004) determined that personalization of the risk was relevant to the public's decision to evacuate. Research in the area of risk perception (Slovic, 1987, Cox, *et al.*, 2003, and others) has shown that while analysts use formal risk assessment methods to evaluate risks, the general public develops different perceptions based on their own understanding and concerns, and that these perceptions are difficult to change (Slovic, 1987). Differences between public and experts' perception of risks need to be reconciled or at least managed to improve compliance with the protective action recommendation. Communication and education may provide a means of managing or mitigating these risks.

Education regarding nuclear risks may require an element of persuasion (Yim & Vaganov, 2003) in order to change people's attitudes. Zhang, *et al.* (2004) suggest that people at risk should be provided sufficient information to convince them they are in danger. It is important that communication of the warning message is both clear and persuasive, describing the threat, the recommended protective action and the potential consequences of not following the official recommendation. Mileti and Sorensen, (1990), assert that the message requires:

- Specificity - A good warning message is specific about the area at risk, what people should do, the character of the hazard, how much time people have to engage in protective actions, and the source of the message.
- Consistency - A warning message must be consistent, both within itself as well as across different messages. Consistency can be rendered across messages in circumstances by simply referencing and repeating what was last said, what has changed, and why.
- Certainty - A message should be stated with certainty even in circumstances in which there is ambiguity associated with the hazard's impact. The warning should be spoken by the person delivering it as if he or she believes or is certain about what is being said.
- Clarity - Warnings must be worded in simple language that can be understood.
- Accuracy - A warning message must contain timely, accurate, and complete information. If people learn or suspect that they are not receiving the whole truth, they may not believe the message.

An effective message is one that convinces people that the threat is real and that the recommended protective action is effective. They must believe in the credibility of the officials issuing the warning and have knowledge on how to effectively implement the protective action.

7.3 Likely Public Acceptance of Shelter-in-Place

Examination of news reports, Federal databases, incident reports and other data indicates that SIP is used effectively by emergency managers across the U.S. The success of SIP in response to chemical hazards would suggest a likely acceptance of this protective action by the public. Whether full compliance might be expected requires additional research. SIP is generally included in the information provided to residents that reside within EPZs in the calendars or brochures. A description of SIP is frequently available on emergency management websites, including instructions on what to do when SIP is ordered.

There are numerous documented cases, as discussed in the previous section, where sheltering was successfully implemented even with little or no public training or awareness. There are also some cases where full compliance for an SIP protective action was not achieved and this affected the success of the protective action. Some research has shown that some people may resist sheltering in place in a radiological incident such as a dirty bomb. Lasker (2004) conducted a telephone survey of more than 2,500 randomly selected households and reported that 60% of respondents stated they would shelter-in-place for as long as told in the event of a dirty bomb and that 20% would not fully cooperate and would leave the shelter of their building to take care of their family or because they felt safer elsewhere. Becker (2004) used focus groups to investigate the public's response to a "weapons of mass destruction" incident and found that many people said they would not do as they were instructed. Observed behavior in numerous SIP incidents has shown that the public does successfully comply with this protective action although full compliance is not always achieved. According to the social psychology community (Quarantelli, 1992a,b, and others), a reason for not achieving full compliance may be that sheltering is not a natural response to an immediate threat. People want to move away from the hazard as quickly as possible. Vogt and Sorensen (1999) found that in situations where both SIP and evacuation had been advised, compliance with SIP was not very high.

It is clear that there are demonstrated cases of SIP with a high compliance rate and there are some cases in which the compliance rate was lower. What is not obvious is what percentage of compliance is necessary to achieve the protection of health and safety of the public that is the objective of emergency response planning. Having some people evacuate, may be beneficial. In discussions with one emergency response manager, it was recognized that providing an early warning of a potential problem, such as at Site Area Emergency, would likely cause some people to evacuate prior to any order to evacuate. This ultimately reduces the number of people that may need to evacuate if the accident were to progress.

7.4 Likely Public Acceptance of Alternate Evacuation Strategies

Acceptance of alternative evacuation strategies is influenced by the emergency response resources available to support the traffic management. For most evacuations, the roadways are blocked at key intersections and the public is directed away from the hazard. Thus, whether the evacuation is lateral or radial is largely dependent on the traffic control established for the area. The NRC study on large scale evacuations, (NRC, 2005b) found that evacuations proceed more smoothly when the public is familiar with the evacuation procedures, the alerting methods being used, and the hazard that caused the evacuation. In addition, cooperative behavior of evacuees was repeatedly cited as contributing to safe, efficient, and effective evacuations. Some additional assumptions regarding evacuation behavior include (Fischer, 1998a,b):

- Households in evacuation areas will evacuate if they are told to do so;
- People are more likely to evacuate if they hear the warning from a family member, friend, or authority figure rather than just from the media;
- Families headed by elderly persons, or extended family households containing elderly persons, are less likely to evacuate in response to hazard warnings;
- Households with young children are more likely to evacuate;
- People with higher incomes are more able to and, thus, more likely to evacuate; and
- People living in multi-unit buildings are more likely to evacuate.

Alternative evacuation strategies assessed in this project are lateral and staged evacuations. These strategies have been compared to the baseline protective action of radial evacuation.

Lateral evacuation would require identifying the expected direction of the plume and directing evacuees perpendicular to the plume such that they evacuate the affected area in the shortest distance. This protective action may be initiated immediately or could be implemented following the shelter period. When the public leaves the shelter, they would evacuate in a direction that removes them from the contaminated area as quickly as possible in order to reduce the dose from groundshine and inhalation from resuspension of contamination. During any evacuation, traffic control would be established to physically direct the traffic in the desired direction. There are some sensitivities that should be considered with this protective action including public behavior and wind shifts.

Certain behavioral responses should be taken into consideration when evaluating the lateral evacuation strategy. Zelinsky and Kosinski (1991) found that evacuees tend to move in the direction that minimizes or cancels the effect of the disaster. Furthermore, Helbing *et al.* (2002) found that people have a strong aversion to taking detours or moving opposite to the desired walking direction, even if the direct way is crowded. It is important that alternative evacuation strategies be sensitive to these behavioral tendencies. This was confirmed in discussions with stakeholders in one State where emergency response personnel pointed out that the tendency of the population at a specific site is to travel north or south along the major roadways. Directing an evacuation west, although possible, would be counterintuitive to the communities.

The possibility of a wind shift during a lateral evacuation must also be considered. At sites with high population densities, evacuations can take many hours to complete. In a review of meteorologic data for approximately 10 NPP sites, the wind shifted at least 30 degrees at many sites over a 10 hour period and shifted up to 180 degrees at some sites within the same time period. If the winds shift direction during the evacuation, a lateral evacuation could place some evacuees in the plume path. In addition, a wind shift would require evacuation of the newly affected sectors. Use of lateral evacuation can be beneficial, and some sites have consistent meteorology and prevailing winds that are predictable and make this a viable alternative.

The second alternative evacuation that has been evaluated is staged evacuation. Staged evacuation is the evacuation of one affected area prior to the evacuation of other affected areas. For an EPZ, an example of a staged evacuation might include evacuating the 3.2 km (2 mile) radius around the NPP prior to evacuating the rest of the EPZ. Staged evacuations are common in response to natural and technological hazards. The NRC study on evacuations, (NRC, 2005b) found that 40% of the 50 evacuation cases studied included some staging during the evacuations and theses evacuations were efficiently and effectively implemented. The widely studied and successful Mississauga, Ontario evacuation of over 200,000 people in 1979 is a good example of a large staged evacuation. In response to Hurricane Katrina, a successful staged approach was used to evacuate Plaquemines parish through the northern Louisiana parishes prior to these northern parishes evacuating. The emergency response managers and parish presidents coordinated with each other in issuing their evacuation orders until Plaquemines parish had started evacuating. Discussions with emergency management personnel in both parishes confirmed this coordinated effort facilitated a successful evacuation of this region of Louisiana. The Gulf States have staged evacuation plans to move people from coastal and low lying areas first.

There are demonstrated successes with staged evacuations, but staged evacuations have not been studied extensively. High compliance with staged evacuations been demonstrated (NRC, 2005b), but it may be difficult to achieve full compliance especially when friends and relatives end up in a different stage of the evacuation. A portion of the population in the sectors ordered to SIP may choose to evacuate. This behavior has been documented in the case of a chemical emergency in Arkansas, which found that people chose to evacuate when warnings to evacuate and warnings to SIP were issued in close proximity to one another. In this particular example, an explosion at an herbicide and pesticide packaging plant released a cloud of chemicals. Residents in a 3.2-km (two-mile) area downwind were ordered to evacuate and residents in the 3.2-km to 4.8-km (two- to three-mile) zone were ordered to SIP. However, 27% of those advised to SIP evacuated instead, while 90% of those advised to evacuate complied with that order (Vogt and Sorensen, 1999). In this Arkansas evacuation, it was later learned that many people were confused by the instructions, which further emphasizes the importance of communication. Also, some of the homes were not prepared for SIP and may not have been suitable (e.g., mobile homes and older homes that were not “air tight”). In addition, some people followed environmental cues (smoke and odor), and advice from neighbors and friends, rather than the warnings provided by the authorities.

In summary, high compliance with staged evacuation has been demonstrated, but this has not been studied extensively. Full compliance may not be expected, nor may it be needed to achieve the desired health and safety benefit to the public. Substantial compliance with such a protective action would likely achieve the desired result of reducing traffic to facilitate expedient evacuation of those nearer the hazard. Well planned communication throughout an incident and well designed traffic control plans can help facilitate a successful staged evacuation.

7.5 Shadow Evacuation

Shadow evacuations are a concern for any type of evacuation and are defined as people evacuating outside of the designated evacuation area. Lindell and Barnes (1986), Houts, *et al.* (1984), and many other researchers have observed or investigated shadow evacuations in emergency situations. Mileti (2000) has said that the effect of shadow evacuations should be factored into the emergency plan. However, it can be difficult to determine the significance or magnitude of the shadow evacuation. In the 2005 NRC study of large scale evacuations, (NRC, 2005b) it was determined that shadow evacuations had no statistically significant impact on congregate care center capacity or on the effectiveness of the evacuation. Shadow evacuations occurred in 18 of the 50 case studies and traffic movement was impacted in only five of these large scale evacuations.

Other studies on evacuation response have shown that the public over-responds to evacuations. Lindell and Barnes (1986), for example, surveyed 137 undergraduate students and asked them to predict what they would do for two scenarios: (1) radiation release from a nuclear power plant, and (2) dioxin release from an herbicide factory. Their data suggest that the over-response at Three Mile Island was due, in part, to the confusing and conflicting information disseminated to the public. They recommended providing the public with accurate information and alternative protective actions to avoid over-response. Large-scale hurricane evacuations, most notably Hurricane Rita, 2005, have shown that public over-response and shadow evacuations can have a significant effect on the transportation network and can potentially lead to casualties that may not have occurred in a well planned and implemented evacuation.

Zeigler and Johnson (1984), as well as Johnson (1984), concluded from their research that the public would over-respond to evacuation orders in the event of an NPP accident. This conclusion was based mainly on a telephone survey of Long Island residents conducted in June 1982 that asked them to predict what they would do if there were an emergency at Shoreham Nuclear Power Station in Suffolk County, approximately 100 km (60 mi) east of New York City. Zeigler and Johnson (1984) and Johnson (1984) also did some comparison with the Brunn, *et al.* (1979) post-Three Mile Island telephone survey. They concluded that shadow evacuees beyond the 16-

km (10-mi) EPZ would make it more difficult for those closer to the plant to evacuate quickly.

Sorensen (1986) questioned the assumption of Zeigler and Johnson (1984) that there would be significant shadow evacuations. The conclusions of Sorensen (1986) were based on NUREG / CR-1215 (Flynn, 1979), which included the results of a telephone survey conducted by NRC after the Three Mile Island emergency, and the conclusions of Stephens and Edison (1982), which was an analysis of news media coverage of the Three Mile Island emergency. Sorensen's model suggests that evacuation response is dictated by awareness of risk, personalization of that risk, evaluation of alternative actions, and then deciding a course of action. Therefore, evacuation behavior would be normal and predictable and not based on fear of radiation. Furthermore, Sorensen (1986) concluded that the public would not panic during such an event.

Shadow evacuation is a real phenomenon experienced in large scale evacuations. Shadow evacuations can be controlled or mitigated through better communication, education of the public and traffic control (NRC, 2005a, 1992a). Emergency response agencies are typically focused on getting an immediate message to the affected population, but for large scale events, a clear message must also be provided immediately to those that are not affected.

7.6 Statistical Analysis of Evacuation Data

To support this assessment of the efficacy of alternative protective actions in terms of behavioral and sociological issues, data that was originally collected for NUREG / CR-6864, *Identification and Analysis of Factors Affecting Public Evacuations* (NRC, 2005b) was analyzed with the specific intent of identifying any behavioral trends in the data. As a part of that project, 230 evacuations were identified and 50 of these were analyzed in detail through research and interviews with emergency response personnel familiar with the events. A detailed questionnaire was developed and completed for each of the 50 case studies. Data acquired during that investigation included behavioral factors that are related to this effort. Advanced statistical methods were used to analyze sets of this data in support of this project. Associations to the following variables have been assessed below and additional detail and variables are presented in Appendix C:

- Shadow evacuations;
- Refusal to evacuate; and
- Early evacuation.

These three variables are included herein because they most closely represented the behavioral tendencies of interest to the PAR study.

7.6.1 Shadow Evacuations

Whether or not a shadow evacuation occurred was known for 42 of the 50 evacuations. In 18 cases (36%) a shadow evacuation took place (NRC, 2005b). A logistic regression model was used to test for association between shadow evacuation and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used to test for association between other variables in the data set and shadow evacuation (Derr, 2000).

The chi-squared or likelihood ratio tests identified that the following variables were significantly associated with shadow evacuations. An association does not necessarily prove a causal relationship. The following variables were positively associated with shadow evacuations:

- Public notified by radio and/or television;
- Size of the community;
- Size of the evacuation area;
- People spontaneously evacuating before being told to do so;
- Number of injuries from the hazard;
- Public notified by multiple methods; and
- Communication between field emergency responders and Emergency Operating Center by telephone.

For technological hazard evacuations, a high level of community awareness with evacuation procedures was also associated with shadow evacuations.

The following variables were negatively associated with shadow evacuations (this variable was associated with the absence of shadow evacuations):

- Special problems regarding warning and subsequent citizen action;
- People told to use specific routes; and
- Public buildings used as shelters.

7.6.2 Refusal to Evacuate

Whether or not anyone refused to evacuate was known for 47 evacuations in the data. In 26 cases (55.3%) refusal to evacuate was reported. A logistic regression model was used to test for association between refusal to evacuate and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used to determine any association between variables in the data set and refusal to evacuate (Derr, 2000).

The chi-squared or likelihood ratio tests identified that the following variables had a positive statistically significant association with refusal to evacuate. An association does not necessarily prove a causal relationship.

- Rural communities;
- People spontaneously evacuating before being told to do so;
- Natural disaster evacuation; and
- Staged evacuation.

The variable public notification by a siren was negatively associated with refusal to evacuate. In other words, when people were notified by a siren, there were fewer evacuation refusals.

7.6.3 Early Evacuation

Whether or not people evacuated spontaneously before being told to do so was known for 43 evacuations in the data. In 22 cases (51.2%) an early evacuation took place and in 21 cases

(48.8%) no early evacuation took place. A logistic regression model was used to test for association between early evacuation and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used find for association between other variables in the data set and early evacuation (Derr, 2000).

The regression analyses identified that the following variables had a positive statistically significant association with early evacuations. An association does not necessarily prove a causal relationship. The following variables were positively associated with early evacuations:

- Refusal to evacuate;
- Natural disaster evacuations;
- Shadow evacuations;
- Public shelters used;
- Lower population density during evacuation;
- Public notified by multiple methods;
- Ethnicity, nationality, or age a factor; and
- Larger population.

For technological hazards, specifically, early evacuations were associated with:

- Previous experience with the alerting mechanism;
- Multiple people participating in the decision to evacuate; and
- Number of injuries caused by hazard.

7.7 Summary

The review of literature provides an indication that the efficacy of protective actions can be affected by the response of the public. Understanding the behavioral and sociological issues that contribute to the public response can assist in developing means to mitigate these effects. In developing protective action messaging, information should be conveyed to the public such that they can develop a decision on whether they are at risk. Sociologists noted that differences between public and experts' perception of risks need to be reconciled or at least managed to improve compliance with the protective action recommendation. Communication and education may provide a means of managing or mitigating these risks.

For alternative protective actions such as sheltering, lateral evacuation, and staged evacuation, it is clear there are successful demonstrations for each of these protective actions. But as indicated, full compliance is not always achieved. This may not be an issue, but should be investigated further, as it is not known what percent of compliance would be necessary to achieve the protection of health and safety desired. Finally, shadow evacuation is a real phenomenon experienced in large scale evacuations, but with adequate planning and excellent communications to the public, shadow evacuations can be controlled or mitigated. In many instances, shadow evacuations occur where the public does not perceive they are at risk based on the communication they receive. A clear message must be provided immediately to those members of the public that are not affected.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This project included evaluation of the current NRC PAR guidance contained in Supplement 3 to NUREG-0654 / FEMA-REP-1, Rev. 1, (NRC, 1996) and assessed whether implementation of alternative protective actions could reduce potential health effects in the unlikely event of an NPP accident. To support this assessment, a suite of alternative protective actions was developed, source terms were selected and consequence modeling was performed. This assessment included analysis of three accident conditions including:

- Rapidly progressing accident;
- Progressive accident; and
- No loss of containment accident.

Any core damage accident is highly unlikely, and rapidly progressing accidents are even less likely, but are included in the emergency preparedness planning basis. Four source terms were selected for the consequence modeling with two of the source terms taken from the NUREG-1150 (NRC, 1990a), and two additional source terms were created by using the release values of the first two source terms and adjusting the timing of these source terms. The source terms used include a rapidly evolving source term and a progressively evolving source term. It is not the intent of this report to validate the magnitude or frequency of these source terms. Any accident resulting in core damage is very unlikely, and an accident that fails containment is even less likely. The source terms were only used to create the consequence analysis files for use in determining the relative ranking of alternative protective actions. If future NRC studies conclude that rapidly evolving source terms are not credible then the results of this study may require reconsideration.

This study identified that in scenarios with a rapidly developing event of relatively high magnitude and short duration alternative protective action strategies are capable of significantly reducing consequences. For the remaining source terms ST-1M, ST-2, and ST-2M, there can be benefits of implementing alternative protective actions, but generally radial evacuation performed well. In many instances, alternative protective actions for these source terms are not significantly different than the baseline. For scenarios with longer ETEs, there are some beneficial protective actions that may be considered. Several conclusions have been drawn from the PAR project, including:

- Evacuation should remain the major element of protective action strategies.
- Revision of NUREG-0654, Supplement 3, should be considered.
- The study indicates that consideration should be given to protective action strategies that allow the population to quickly distance themselves from the plant, such as an early or staged evacuation, because under many circumstances this can reduce consequences.
- The study indicates that precautionary preparation efforts during Site Area Emergency are prudent.
- The study indicates that under the specific accident sequences assessed, consequences increase as the ETE increases; thus, strategies that reduce evacuation times reduce consequences.
- The study indicates that use of ETEs during the emergency planning process is important for assessing the most appropriate protective action (e.g., for each protective action or each set of sectors that may be evacuated).

- The study indicates that shelter-in-place followed by evacuation is more protective than immediate evacuation for rapidly developing releases for sites with longer evacuation times. Consideration should be given to further site specific development of supporting PARs.
- The study indicates that sheltering of special needs individuals followed by evacuation can result in fewer consequences under select conditions.
- The study documents several potential enhancements to communication processes used during emergencies. It may be appropriate to publish these enhancements for consideration by the emergency response community.
- The study and other ongoing studies indicate that special needs populations that do not reside in special facilities may be under served in evacuation planning. It appears that this issue warrants further investigation and development of guidance on this issue may be appropriate.

The effectiveness of PAR strategy is sensitive to both initial release timing and the ETE, and therefore, it is important to reduce the uncertainties associated with each of these parameters. Improving the accuracy and quality of ETE values would support assurance that the most appropriate protective action has been recommended. For sites with short ETEs the PAR study concludes that evacuation is the most appropriate recommendation for any accident scenario, barring constraints such as adverse weather. For sites with longer ETEs, immediate radial evacuation is not the appropriate recommendation for large early release accident scenarios. An early result of this project, based largely on the result of the research conducted on ETEs is that NRC is pursuing rule making to enhance ETEs.

The PAR study analyzed a hypothetical site, which does not depict any actual site. Under the assumptions of the PAR study, it appears that for sites with ETEs longer than 4 hours initial sheltering for rapidly progressing scenarios may be beneficial. It would be appropriate during emergency planning for licensees to conduct an ETE for each PAR considered, such as those that include an initial sheltering protective action. Additionally, it may be appropriate for licensees to conduct a consequence assessment to determine the site specific break point for evacuation versus sheltering based upon release timing and the time to evacuate specific areas. Although 4 hours was identified in this study of a uniformly distributed population, many sites have small populations within 8.0 km (5 miles) of the site, thus a site specific analysis would be necessary.

Protective action strategies that reduce evacuation times, including earlier implementation of protective actions, can reduce consequences. Early and staged evacuations provide alternatives that have the effect of moving the public away from the source term in an expeditious manner. Many States already institute some level of early protective actions such as the movement of school children at Site Area Emergency. Expanding on this concept with staged evacuations can reduce potential consequences.

NUREG-0654, Supplement 3, states that for all but a very limited set of conditions, prompt evacuation of the area near the plant is much more effective in reducing the risk of early health effects than sheltering the population in the event of a severe accident. Supplement 3 provides guidance that licensees recommend evacuation of a two mile ring and five miles downwind for severe accidents, with sheltering considered for unique instances such as severe weather. This has typically been implemented in a manner that any General Emergency is considered a severe accident. The PAR Study has shown that sheltering is a better option under some circumstances. More specific guidance on the use of sheltering should be integrated into Supplement 3 as well as criteria for the implementation of the subsequent evacuation that may follow a sheltering event.

The conclusions from this study support the following protective action strategies when appropriately selected for the incident:

- Immediate evacuation;
- Shelter-in-place;
- Staged evacuation;
- Preferential sheltering for special needs individuals;
- Delayed evacuation, until traffic controls are in place;
- Early closure of schools, parks, beaches, and government facilities at the Site Area Emergency;
- Consideration of early protective actions within the 3.2-km (2-mile) radius surrounding the plant at Site Area Emergency; and
- Early notification of the general population within the 10-mile EPZ to prepare for evacuation.

Preferential sheltering, which is the use of larger facilities that afford better shielding than normal residence, was deemed unfeasible. The benefit achieved through this protective action was not significantly more protective than evacuation.

Lateral evacuation is an effective evacuation strategy when meteorologic conditions are such that wind direction does not change. NRC guidance may be developed to provide sites the flexibility to consider lateral evacuation during both immediate evacuation and the evacuation following a sheltering event. However, emergency response plans would need to address the potential problems associated with this strategy, including the probability that the wind direction may change, potential public resistance, configuration of the existing roadway network, and the capacity of those roadways to handle a greater load during an evacuation.

For events where the protective action guides are expected to be exceeded, some type of evacuation strategy would be the preferred PAR, barring any constraints to evacuation. For these events, immediate evacuation is best if it can be completed in less than 4 hours. In all cases, staged evacuation results in fewer consequences than a standard radial evacuation, however, in some instances the benefit was not pronounced.

8.1 Rapidly Progressing Accident

These modeling results indicate that in scenarios with a rapidly developing event of relatively high magnitude and short duration alternative protective action strategies are capable of reducing consequences. For ST-1, all of the alternative protective actions performed better than the baseline of evacuation. For rapidly progressing events such as ST-1, evacuation is the preferred protective action only if it can be completed in less than 4 hours. This should be a site-specific decision as there are some sites with longer ETEs, but with very few people living within 8 km (5 miles) of the plant. When evacuation can not be completed in a short time, shelter-in-place until the plume has passed followed by evacuation results in fewer consequences than standard radial evacuation.

8.2 Progressive Accident

For releases of lesser magnitude and greater warning time, such as ST-1M, ST-2, and ST-2M, benefits from alternative protective actions would be more site specific because the benefits are frequently dependent on the ETE and the ability to conduct a lateral evacuation. The staged evacuation alternative resulted in fewer early and late consequences than the constant-speed evacuation scenario, indicating that it may be beneficial to take measures that will increase evacuation speed at early times. These measures might include staging the evacuation to allow certain at-risk populations to evacuate more quickly.

8.3 No Loss of Containment Accident

In a no loss of containment accident, the leakage through the containment structure can be great enough to exceed the threshold for evacuation. The evacuation threshold at the 3.2 km (2 mile) boundary can be exceeded in 8 hours at a rate of 0.5% per day. Exceeding the evacuation threshold would take longer for leakages of lesser magnitude. Because of the slow rates of leakage, the evacuation threshold at points farther from the plant take even longer and can be greater than 24 hours at the 16 km (10 mile) EPZ boundary providing ample time for the implementation of protective actions.

8.4 General Conclusions

The results of the PAR study support a recommendation for the update of the "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants", NUREG-0654 / FEMA-REP-1, Rev. 1, Supplement 3 (NRC, 1996). This study confirmed, as stated in Supplement 3, that for all but a very limited set of conditions, prompt evacuation of the area near the plant is much more effective in reducing the risk of early health effects than sheltering the population in the event of severe accidents. However, an update to Supplement 3 should be provided to address the following items.

- Clarification on the conditions for which shelter-in-place is effective;
- Clarification and guidance on the importance of having a means to track the plume passage; communicate with those sheltered, and then direct an effective evacuation immediately upon the termination of the shelter event;
- Emphasize the benefits of staged evacuation;
- Consider expanding the initial guidance to address the full 10 mile EPZ rather than 0-5 miles as currently expressed; and
- Clarify the shelter guidance and expectations for the transit dependent persons.

The update of Supplement 3 would clarify the existing direction on the appropriateness of sheltering and alternative protective actions such that the development of protective actions will consider the breadth of available options within the context of site specific considerations.

Studies of recent large scale evacuations have provided valuable insights on the evacuation of the permanent population, special facilities, and the transient population. The lessons learned from these evacuations are being integrated into emergency response planning and guidance documentation. The population that is dependent on public transportation requires added detail in emergency response planning to assure all members of this population group are identified and adequate resources are available to support their evacuation. Including additional detail and sound assumptions in ETE studies when calculating the time for return trips and delays that may be encountered when traveling against the prevailing evacuating traffic adds value to the time estimates.

A population group that may be under served, includes those individuals with special needs who do not reside in special facilities. Improvements in identifying this population group and securing the resources necessary to support evacuation should be included in emergency response planning for EPZs. Proactive efforts to identify special needs individuals have proven to be beneficial in some States. These efforts may be grass roots where information is elicited from churches, community centers, and similar congregation areas.

8.5 Recommendations

The results of the PAR study support consideration of revision of Supplement 3, NUREG-0654/FEMA-REP-1, Rev. 1, (NRC, 1996). This study confirmed, as stated in Supplement 3, that for all but a very limited set of conditions, prompt evacuation of the area near the plant is much more effective in reducing the risk of early health effects than sheltering the population in the event of severe accidents. A revision to Supplement 3 should consider addressing the following items.

- Clarification of the conditions for which shelter-in-place is effective.
- Clarification and guidance on the importance of having a means to track the plume passage, communicate with those sheltered, and then direct an effective evacuation immediately upon the termination of the shelter event.
- Emphasize the benefits of staged evacuation.
- Clarify the shelter guidance and expectations for the transit dependent persons.

Any future revision to Supplement 3 would benefit from a publicly observed process involving stakeholder input. The objective of such a revision would be to foster development of protective actions that include the breadth of available options within the context of site specific considerations.

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Appendix A

Source Terms for Off-Site Consequence Analysis

Source Term 1: Interfacing System Loss of Coolant Source Term

Containment Failure: Submerged interfacing system pipe break

Containment Sprays: Do not remove fission products during release

Core-Concrete Interacting (CCI): Dry interaction takes place promptly after vessel breach

Reactor Coolant System (RCS) Pressure: Less than 200 psia

Vessel Breach Mode: Gravitational pour of molten core

Steam Generator Tube Rupture: None

Amount of core available for CCI: >70%

Zirconium Oxidation: Low

High Pressure Melt Ejection: None

Containment Failure Size: None

Holes in the RCS: One large hole

Warning time: $1.3x10^{3}$ seconds

Elevation: 0.0 meters

Quantity	**First Release**	**Second Release**
Energy (W)	$1.9x10^{6}$	$1.7x10^{5}$
Start Time (s)	$3.7x10^{3}$	$1.0x10^{4}$
Duration (s)	$1.8x10^{3}$	$2.2x10^{4}$
Core Inventory Fractional Release		
Noble Gas	$9.9x10^{-1}$	$1.1x10^{-2}$
Halogen Group – I	$7.0x10^{-2}$	$4.7x10^{-2}$
Alkali Metals Group – Cs	$7.1x10^{-2}$	$7.6x10^{-3}$
Tellurium Group – Te	$9.4x10^{-3}$	$3.3x10^{-2}$
Strontium Group – Sr	$2.4x10^{-3}$	$1.1x10^{-2}$
Noble Metals Group – Ru	$4.3x10^{-4}$	$3.1x10^{-4}$
Lanthanides Group- La	$1.2x10^{-4}$	$1.3x10^{-3}$
Cerium Group – Ce	$5.5x10^{-4}$	$1.4x10^{-3}$
Barium Group – Ba	$2.7x10^{-3}$	$9.3x10^{-3}$

For consistency this tellurium group release is quoted directly from the NUREG-1150 data and does not include the 2-3 fold increase suggested by the recent literature.

Source Term 2: Fire with Containment Venting Source Term

Accident Sequence: Fire Initiated

Core Damage Time: 28 hours after initiating event

Zirconium Oxidation: <21%

Vessel Condition at Vessel Breach: Low Pressure

Direct Containment Heating: 5% of core involved in ex-vessel steam explosions

Containment Failure Before Vessel Breach: Vented

Containment Failure at Vessel Breach: Wetwell leak below the water line

Late Containment Failure: No failure

Containment Sprays: No operation

Core-Concrete Interaction: Dry interaction in pedestal cavity

Safety Relief Valve Operation: All in-vessel releases discharged into suppression pool

Suppression Pool Bypass: Reactor cavity floor fails several hours after vessel breach

Station Blackout: No station blackout

Warning time: $8.9x10^4$ seconds

Elevation: 30.0 meters

Quantity	**First Release**	**Second Release**	**Third Release**
Energy (W)	$9.4x10^6$	$1.7x10^7$	$2.2x10^7$
Start Time (s)	$1.0x10^5$	$1.2x10^5$	$1.2x10^5$
Duration (s)	$1.5x10^4$	$9.0x10^2$	$2.2x10^4$
Core Inventory Fractional Release			
Noble Gas	$7.1x10^{-1}$	$1.5x10^{-2}$	$2.8x10^{-1}$
Halogen Group – I	$5.6x10^{-3}$	$1.5x10^{-3}$	$1.4x10^{-1}$
Alkali Metals Group – Cs	$3.8x10^{-3}$	$2.2x10^{-3}$	$1.4x10^{-1}$
Tellurium Group – Te	$2.1x10^{-3}$	$7.3x10^{-4}$	$9.2x10^{-2}$
Strontium Group – Sr	$6.9x10^{-4}$	$3.9x10^{-4}$	$7.8x10^{-2}$
Noble Metals Group – Ru	$9.0x10^{-5}$	$4.2x10^{-4}$	$1.9x10^{-4}$
Lanthanides Group – La	$3.0x10^{-5}$	$9.8x10^{-5}$	$7.9x10^{-3}$
Cerium Group – Ce	$1.2x10^{-4}$	$9.6x10^{-5}$	$1.2x10^{-2}$
Barium Group – Ba	$7.1x10^{-4}$	$4.6x10^{-4}$	$6.5x10^{-2}$

Appendix B

MACCS2 Results

The following tables were respectfully normalized according to total sum of early fatalities (EF) and latent cancer fatalities (LCF). Early fatalities and latent cancer fatalities were calculated assuming a population density of 100 people per square kilometer in the 16-km EPZ.

Table 5.1A. Source Term ST-1, 4-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
Staged Evacuation	0	0.10
PS-2 hrs/Lateral Evac	0.03	0.05
PS-2 hrs/Radial Evac	0.04	0.06
PS-4 hrs/Lateral Evac	0.05	0.04
PS-4 hrs/Radial Evac	0.05	0.05
PS-8 hrs/Lateral Evac	0.05	0.05
SIP-2 hrs/Lateral Evac	0.06	0.07
PS-8 hrs/Radial Evac	0.07	0.07
SIP-4 hrs/Lateral Evac	0.07	0.06
SIP-4 hrs/Radial Evac	0.07	0.07
SIP-8 hrs/Radial Evac	0.10	0.09
SIP-8 hrs/Lateral Evac	0.11	0.08
SIP-2 hrs/Radial Evac	0.11	0.09
Radial Evacuation (Constant Speed)	0.19	0.13

Table 5.1B. Source Term ST-1, 6-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
PS-2 hrs/Lateral Evac	0.03	0.05
PS-2 hrs/Radial Evac	0.03	0.06
PS-4 hrs/Lateral Evac	0.04	0.04
PS-4 hrs/Radial Evac	0.04	0.05
PS-8 hrs/Radial Evac	0.06	0.06
SIP-4 hrs/Lateral Evac	0.06	0.06
PS-8 hrs/Lateral Evac	0.06	0.06
SIP-4 hrs/Radial Evac	0.06	0.07
SIP-2 hrs/Lateral Evac	0.06	0.07
Staged Evacuation	0.07	0.12
SIP-2 hrs/Radial Evac	0.08	0.09
SIP-8 hrs/Radial Evac	0.09	0.08
SIP-8 hrs/Lateral Evac	0.09	0.07
Radial Evacuation (Constant Speed)	0.24	0.13

Table 5.1C. Source Term ST-1, 8-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
PS-2 hrs/Lateral Evac	0.03	0.05
PS-2 hrs/Radial Evac	0.03	0.06
PS-4 hrs/Lateral Evac	0.03	0.04
PS-4 hrs/Radial Evac	0.04	0.05
PS-8 hrs/Radial Evac	0.05	0.06
SIP-4 hrs/Lateral Evac	0.05	0.06
PS-8 hrs/Lateral Evac	0.05	0.05
SIP-4 hrs/Radial Evac	0.06	0.07
SIP-2 hrs/Lateral Evac	0.06	0.08
SIP-2 hrs/Radial Evac	0.07	0.09
SIP-8 hrs/Radial Evac	0.08	0.07
SIP-8 hrs/Lateral Evac	0.08	0.07
Staged Evacuation	0.13	0.12
Radial Evacuation (Constant Speed)	0.24	0.13

Table 5.1D. Source Term ST-1, 10-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
PS-2 hrs/Lateral Evac	0.03	0.05
PS-2 hrs/Radial Evac	0.03	0.06
PS-4 hrs/Lateral Evac	0.03	0.04
PS-4 hrs/Radial Evac	0.04	0.05
PS-8 hrs/Radial Evac	0.05	0.06
SIP-4 hrs/Lateral Evac	0.05	0.06
PS-8-hrs/Lateral Evac	0.05	0.05
SIP-2 hrs/Lateral Evac	0.06	0.08
SIP-4 hrs/Radial Evac	0.06	0.07
SIP-8 hrs/Radial Evac	0.08	0.07
SIP-8 hrs/Lateral Evac	0.08	0.07
SIP-2 hrs/Radial Evac	0.08	0.09
Staged Evacuation	0.15	0.12
Radial Evacuation (Constant Speed)	0.24	0.13

Table 5.2A. Source Term ST-2, 4-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs Lateral Evac	0	0.00
Staged Evacuation	0	0.00
Radial Evacuation (constant speed)	0	0.00
SIP-2 hrs/Radial Evac	0	0.01
SIP-4 hrs/Lateral Evac	0	0.01
PS-4 hrs Lateral Evac	0	0.01
PS-2 hrs/Radial Evac	0.00	0.01
SIP-4 hrs/Radial Evac	0.00	0.02
SIP-8 hrs/Lateral Evac	0.00	0.03
PS-4 hrs/Radial Evac	0.00	0.03
PS-8 hrs/Lateral Evac	0.00	0.12
SIP-8 hrs/Radial Evac	0.00	0.32
PS-8 hrs/Radial Evac	1.00	0.45

Table 5.2B. Source Term ST-2, 6-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
Staged Evacuation	0.00	0.00
Radial Evacuation (constant speed)	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.00
PS-4 hrs/Lateral Evac	0	0.01
SIP-2 hrs/Radial Evac	0	0.01
PS-2 hrs/Radial Evac	0	0.02
SIP-8 hrs/Lateral Evac	0	0.04
SIP-4 hrs/Radial Evac	0	0.04
PS-4 hrs/Radial Evac	0	0.07
PS-8 hrs/Lateral Evac	0	0.10
SIP-8 hrs/Radial Evac	0.06	0.31
PS-8 hrs/Radial Evac	0.94	0.38

Table 5.2C. Source Term ST-2, 8-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.00
PS-4 hrs/Lateral Evac	0	0.00
Staged Evacuation	0	0.01
Radial Evacuation (constant speed)	0	0.01
SIP-2 hrs/Radial Evac	0.00	0.03
PS-2 hrs/Radial Evac	0.00	0.04
SIP-8 hrs/Lateral Evac	0.00	0.05
SIP-4 hrs/Radial Evac	0.00	0.08
PS-8 hrs/Lateral Evac	0.00	0.09
PS-4 hrs/Radial Evac	0.00	0.11
SIP-8 hrs/Radial Evac	0.17	0.27
PS-8 hrs/Radial Evac	0.83	0.31

Table 5.2D. Source Term ST-2, 10-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.00
PS-4 hrs/Lateral Evac	0	0
Staged Evacuation	0	0.02
Radial Evacuation (constant speed)	0	0.03
SIP-2 hrs/Radial Evac	0	0.05
SIP-8 hrs/Lateral Evac	0	0.05
PS-2 hrs/Radial Evac	0	0.07
PS-8 hrs/Lateral Evac	0	0.08
SIP-4 hrs/Radial Evac	0	0.11
PS-4 hrs/Radial Evac	0	0.13
SIP-8 hrs/Radial Evac	0.26	0.23
PS-8 hrs/Radial Evac	0.74	0.24

Table 5.3A, Source Term ST-1m, 4-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
Staged Evacuation	0.00	0.01
Radial Evacuation (constant speed)	0.00	0.02
PS-2 hrs/Lateral Evac	0.00	0.04
PS-4 hrs/Lateral Evac	0.03	0.06
SIP-2 hrs/Radial Evac	0.03	0.11
PS-4 hrs/Radial Evac	0.04	0.08
PS-8 hrs/Radial Evac	0.07	0.07
PS-8 hrs/Lateral Evac	0.07	0.06
SIP-4 hrs/Lateral Evac	0.1	0.09
SIP-8 hrs/Radial Evac	0.12	0.09
SIP-8 hrs/Lateral Evac	0.12	0.08
SIP-4 hrs/Radial Evac	0.20	0.12
PS-2 hrs/Radial Evac	0.23	0.15

Table 5.3B. Source Term ST-1m, 6-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.01
PS-2 hrs/Lateral Evac	0.00	0.06
Staged Evacuation	0.00	0.04
Radial Evacuation (constant speed)	0.01	0.07
PS-4 hrs/Lateral Evac	0.02	0.06
PS-4 hrs/Radial Evac	0.03	0.07
PS-8 hrs/Radial Evac	0.05	0.06
PS-8 hrs/Lateral Evac	0.05	0.05
SIP-8 hrs/Radial Evac	0.1	0.07
SIP-8 hrs/Lateral Evac	0.1	0.06
SIP-4 hrs/Lateral Evac	0.10	0.08
SIP-2 hrs/Radial Evac	0.12	0.12
SIP-4 hrs/Radial Evac	0.14	0.1
PS-2 hrs/Radial Evac	0.29	0.13

Table 5.3C. Source Term ST-1m, 8-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.03
Staged Evacuation	0.01	0.07
PS-2 hrs/Lateral Evac	0.01	0.08
PS-4 hrs/Lateral Evac	0.02	0.05
PS-4 hrs/Radial Evac	0.03	0.06
Radial Evacuation (constant speed)	0.03	0.09
PS-8 hrs/Lateral Evac	0.05	0.05
PS-8 hrs/Radial Evac	0.05	0.05
SIP-8 hrs/Lateral Evac	0.09	0.06
SIP-8 hrs/Radial Evac	0.09	0.07
SIP-4 hrs/Lateral Evac	0.09	0.08
SIP-4 hrs/Radial Evac	0.11	0.09
SIP-2 hrs/Radial Evac	0.16	0.11
PS-2 hrs/Radial Evac	0.27	0.11

Table 5.3D. Source Term ST-1m, 10-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.0	0.05
Staged Evacuation	0.0	0.08
PS-4 hrs/Lateral Evac	0.0	0.05
PS-4 hrs/Radial Evac	0	0.06
PS-8 hrs/Lateral Evac	0	0.04
PS-8 hrs/Radial Evac	0	0.05
Radial Evacuation (constant speed)	0	0.10
PS-2 hrs/Lateral Evac	0.1	0.09
SIP-8 hrs/Lateral Evac	0.1	0.05
SIP-8 hrs/Radial Evac	0.1	0.06
SIP-4 hrs/Lateral Evac	0.1	0.08
SIP-4 hrs/Radial Evac	0.1	0.09
SIP-2 hrs/Radial Evac	0.2	0.11
PS-2 hrs/Radial Evac	0.2	0.11

Table 5.4A. Source Term ST-2m, 4-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
Staged Evacuation	0.00	0.00
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
Radial Evacuation (constant speed)	0.00	0.00
PS-4 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.01
SIP-2 hrs/Radial Evac	0.00	0.01
PS-2 hrs/Radial Evac	0.00	0.02
SIP-4 hrs/Radial Evac	0.00	0.04
PS-4 hrs/Radial Evac	0.00	0.07
SIP-8 hrs/Lateral Evac	0.20	0.14
PS-8 hrs/Lateral Evac	0.15	0.15
PS-8 hrs/Radial Evac	0.3	0.28
SIP-8 hrs/Radial Evac	0.35	0.28

Table 5.4B. Source Term ST-2m, 6-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
PS-4 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0	0.01
Staged Evacuation	0	0.01
Radial Evacuation (constant speed)	0	0.01
SIP-2 hrs/Radial Evac	0	0.03
PS-2 hrs/Radial Evac	0	0.04
SIP-4 hrs/Radial Evac	0	0.08
PS-4 hrs/Radial Evac	0	0.11
SIP-8 hrs/Lateral Evac	0.17	0.12
PS-8 hrs/Lateral Evac	0.13	0.12
PS-8 hrs/Radial Evac	0.33	0.23
SIP-8 hrs/Radial Evac	0.38	0.24

Table 5.4C. Source Term ST-2m, 8-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.00
PS-4 hrs/Lateral Evac	0.00	0.01
Staged Evacuation	0.00	0.01
Radial Evacuation (constant speed)	0.00	0.02
SIP-2 hrs/Radial Evac	0.00	0.05
PS-2 hrs/Radial Evac	0	0.07
SIP-8 hrs/Lateral Evac	0.14	0.10
PS-8 hrs/Lateral Evac	0.11	0.10
SIP-4 hrs/Radial Evac	0	0.11
PS-4 hrs/Radial Evac	0	0.13
PS-8 hrs/Radial Evac	0.34	0.19
SIP-8 hrs/Radial Evac	0.41	0.2

Table 5.4D. Source Term ST-2m, 10-hour ETE

Protective Action	EF Normalized to the Total Sum EF	LCF Normalized to the Total Sum of LCF
SIP-2 hrs/Lateral Evac	0.00	0.00
PS-2 hrs/Lateral Evac	0.00	0.00
SIP-4 hrs/Lateral Evac	0.00	0.01
PS-4 hrs/Lateral Evac	0.00	0.01
Staged Evacuation	0.00	0.02
Radial Evacuation (constant speed)	0.00	0.04
SIP-2 hrs/Radial Evac	0.00	0.08
PS-2 hrs/Radial Evac	0.00	0.09
SIP-8 hrs/Lateral Evac	0.12	0.09
PS-8 hrs/Lateral Evac	0.10	0.09
SIP-4 hrs/Radial Evac	0.00	0.11
PS-4 hrs/Radial Evac	0.01	0.13
PS-8 hrs/Radial Evac	0.35	0.15
SIP-8 hrs/Radial Evac	0.42	0.16

Appendix C

Statistical Analysis of Evacuation Data

Statistical Analysis of Evacuation Data

To support the assessment of the efficacy of alternative protective actions in terms of behavioral and sociological issues, data that was originally collected for NUREG / CR-6864, *Identification and Analysis of Factors Affecting Public Evacuations* (NRC, 2005b) was evaluated with specific consideration of parameters important to this PAR study. Complete descriptions of the parameters assessed can be found in NUREG / CR-6864. Appendix C contains a detailed break-down of important variables that showed a statistical or marginally statistical association to the following variables from the evacuation study (NRC, 2005b):

- Shadow evacuations;
- Refusal to evacuate; and
- Early evacuation.

Independent analyses were performed for the above, and since hazard type is often associated with other variables, the results were adjusted for hazard type. Each variable in the questionnaire was compared to each of the variables listed above, and the resulting chi-squared value (probability or p-value) from the likelihood ratio tests were performed to test if each variable was significantly associated with each of the "behavioral" variables.

In the analysis, a p-value is the probability of observing the difference in the data by random chance. Thus, if $p<0.05$, there is less than a 5% chance that this association would have occurred if there were no association, and the hypothesis that there is no association is rejected in favor of the hypothesis that there is an association. A variable with a p-value of less than 0.05 is considered to have a statistically significant association to the efficiency score. If the p-value is between 0.05 and 0.10, the variable is considered to have a marginal (or weak) statistical association to the efficiency score. A $p<0.01$ is considered to show a highly significant statistical association.

The absence of a significant association does not necessarily imply that no association is present, especially given the fact that sample sizes are small there may simply not be enough data for the association to be detected. For missing data, pairwise deletion of missing values was used, which is the most common method of handling missing data. Statistical Analysis System version 8.2 (Derr, 2000) was used for all calculations.

C.1 Shadow Evacuations

Whether or not people evacuated from areas outside the designated area was known for 42 of the 50 evacuations. In 18 cases (42.9%) a shadow evacuation took place and in 24 cases (57.1%) no shadow evacuation took place. A logistic regression model was used to test for association between shadow evacuation and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used to test for association between other variables in the dataset and shadow evacuation (Derr, 2000).

Was public notified by radio/TV?
Overall, there is a highly significant positive association between this variable and shadow evacuations, $p=0.00052$. There is also a highly significant positive association between this variable and shadow evacuations after adjusting for hazard type, $p=0.0015$. When the public was

notified by radio or television, 74% of the evacuations had a shadow evacuation. Whereas when the public was not notified by radio or television, only 18% of the evacuations had a shadow evacuation. For natural disaster evacuations, this variable is also highly associated with there being a shadow evacuation, p=0.0008. In all 8 natural disaster evacuations where the public was notified by radio or television there were shadow evacuations. In none of the five natural disaster evacuations where the public was not notified by radio or television was there a shadow evacuation. In technological disaster evacuations, this variable is associated with shadow evacuations, p=0.046. For technological disaster evacuations when the public was notified by radio or television, there were shadow evacuations 60% of the time, and when the public was not notified by radio or television, there were shadow evacuations only 19% of the time.

Community area

Overall, there is a highly significant positive association between community area and shadow evacuations, p=0.0012. After adjusting for hazard type there is a significant positive association between size of the community (i.e., land area) and shadow evacuations, p=0.048. In general, the larger communities have a greater chance of having shadow evacuations. Breaking down by hazard type, there is a significant positive association for technological hazard evacuations, p=0.0395 but no significant association for natural disaster evacuations, p=0.5152.

Evacuation area

Overall, there is a highly significant positive association between this variable and shadow evacuations, p=0.0025. After adjusting for hazard type there is a marginally significant positive association between evacuation area and shadow evacuations, p=0.058. In general the bigger area evacuated the higher the likelihood that there will be shadow evacuations. When the data are broken down by hazard type, there is no significant associations, p=0.28 for technological hazard evacuations and p=1.0 for natural disaster evacuations.

Did some people spontaneously evacuate before being told to do so?

Overall, there is a highly significant positive association between this variable and shadow evacuations, p=0.0029. There is also a highly significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.0054. If some people spontaneously evacuated before being told to do so, 72% of the time there was a shadow evacuation. If people did not spontaneously evacuate before being told to do so, 21% of the time there was a shadow evacuation. There was not a significant association between this variable and shadow evacuation for natural disasters, p=0.13. However, a lack of a significant association does not mean that the association is not in fact present in the population. The sample sizes are small when the data are broken down by hazard type. There are only 13 natural disaster evacuations where shadow evacuation status is known, and of these 13 natural disasters, there are only 2 evacuations where people did not evacuate early. For technological hazard evacuations, this variable is marginally positively associated with shadow evacuations, p=0.052.

Time to complete the evacuation

Overall, there is a significant positive association between time to complete the evacuation and shadow evacuations, p=0.0037. However, after adjusting for hazard type this association is no longer significant, p=0.10. When the data are broken down by hazard type, there are no significant associations, p=0.83 for technological hazard evacuations and p=0.40 for natural disaster evacuations.

Proximity to a nuclear power plant
Overall, there is a highly significant positive association between this variable and shadow evacuations, p=0.0049. There is also a significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.016. Not surprisingly this association seems to stem from the technological hazard evacuations. There is not significant association for natural disaster evacuations, p=0.31. For technological hazard evacuations there is a significant association, p=0.022. There was only one technological hazard evacuation within 16 kilometers of a nuclear power plant and in that evacuation there was a shadow evacuation. There was a shadow evacuation in none of the technological hazard evacuations within 17-80 kilometers of a nuclear power plant and there was a shadow evacuation in 42% of technological hazard evacuations over 80 kilometers from a nuclear power plant.

Number of injuries from the hazard
Overall, there is a significant positive association between number of injuries from the hazard and shadow evacuations, p=0.0080. There is also a significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.0023. For natural disaster evacuations there is not a significant association between this variable and shadow evacuations, p=1.0. For technological hazard evacuations there is a significant positive association, p=0.014.

Was public notified by multiple methods?
Overall, there is a highly significant positive association between this variable and shadow evacuations, p=0.0082. There is also a highly significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.0090.

For natural disaster evacuations there is a highly significant positive association between this variable and shadow evacuations, p=0.0070. For technological hazard evacuations there is a marginally significant positive association, p=0.098.

Were people told to use specific routes?
Overall, there is a highly significant negative association between this variable and shadow evacuations, p=0.0049. There is a marginally significant negative association between this variable and shadow evacuations after adjusting for hazard type, p=0.037.

There is not significant association for natural disaster evacuations, p=0.59. For technological hazard evacuations there is a marginally significant negative association, p=0.059.

Were political boundaries crossed?
Overall, there is a significant positive association between this variable and shadow evacuations, p=0.012. There is also a significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.032.

For natural disaster evacuations there is a highly significant positive association between this variable and shadow evacuations, p=0.0070. For technological hazard evacuations there is not a significant association, p=0.65.

Ethnicity, nationality or age important?
Overall, there is a significant positive association between this variable and shadow evacuations, p=0.015. There is also a significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.014.

For natural disaster evacuations there is a marginally significant positive association between this variable and shadow evacuations, p=0.081. For technological hazard evacuations there is not a significant association, p=0.11.

Number of evacuations
Overall, there is a significant positive association between this variable and shadow evacuations, p=0.017. However, after adjusting for hazard type this association is no longer significant, p=0.4025. When the data are broken down by hazard type, there are no significant associations, p=0.58 for technological hazard evacuations and p=0.39 for natural disaster evacuations.

Elapsed time between start of hazard and decision to evacuate
Overall, there is a significant positive association between elapsed time between start of hazard and decision to evacuate and shadow evacuations, p=0.018. However, after adjusting for hazard type this association is no longer significant, p=0.12. When the data are broken down by hazard type, there are no significant associations, p=0.37 for technological hazard evacuations and p=0.18 for natural disaster evacuations.

Type of community
Overall, there is a significant association between this variable and shadow evacuations, p=0.038. There is also a marginally significant association between this variable and shadow evacuations after adjusting for hazard type, p=0.094. Thirty-two percent of the evacuations that took place in a city had shadow evacuations, 86% of the evacuations that took place in a county had shadow evacuations, 50% of the evacuations that took place in a town had shadow evacuations and none of the two evacuations that took place in another type of community had a shadow evacuation. There is a marginal association for natural disaster evacuations, p=0.086. None of the three natural disaster evacuations that took place in a city had a shadow evacuation, 86% of the natural disaster evacuations that took place in a county had shadow evacuations and 67% of the natural disaster evacuations that took place in a county had shadow evacuations. Note that all county evacuations were natural disaster evacuations. For technological hazard evacuations there is not a significant association, p=1.0.

Were public buildings used as shelters?
Overall, there is a significant negative association between this variable and shadow evacuations, p=0.039. There is also a significant negative association between this variable and shadow evacuations after adjusting for hazard type, p=0.031. For natural disaster evacuations there is a significant negative association between this variable and shadow evacuations, p=0.018. For technological hazard evacuations there is not a significant association, p=0.60.

Any special problems regarding warning and subsequent citizen action?
Overall, there is a marginally significant negative association between this variable and shadow evacuations, p=0.055. When there were special problems regarding warning and subsequent citizen action there were shadow evacuations 11% of the time, when there were no special problems there were shadow evacuations 52% of the time. There is also a significant negative association between this variable and shadow evacuations after adjusting for hazard type, p=0.012. For natural disaster evacuations there is a significant negative association between this variable and shadow evacuations, p=0.032. For technological hazard evacuations there is not a significant association, p=0.27.

Was public notified door-to-door?
Overall, there is a marginally significant positive association between this variable and shadow evacuations, p=0.075. There is also a significant positive association between this variable and shadow evacuations after adjusting for hazard type, p=0.040. No significant associations where observed when broken down by hazard type, p=0.22 for natural disaster evacuations and p=0.38 for technological hazard evacuations.

Was an EOC used?
Overall, there is a marginally significant positive association between this variable and shadow evacuations, p=0.095. However, after adjusting for hazard type this association is no longer significant or marginally significant, p=0.41. An EOC was always used in natural disaster evacuations. For technological hazard evacuations there is not a significant association, p=0.41.

Any special characteristics?
For natural disaster evacuations there is a significant positive association between this variable and shadow evacuations, p=0.035.

If an exercise was performed, what type of exercise was performed immediately prior to this evacuation?
For natural disaster evacuations there is a significant association between this variable and shadow evacuations, p=0.029. For natural disaster evacuations when a FSFE/TT evacuation was performed 100% of the evacuations had a shadow evacuation. For natural disaster evacuations where a FD or FSFE training alone occurred, 0% of the evacuations had a shadow evacuation.

Were schools used as shelters?
For natural disaster evacuations there is a marginally significant positive association between this variable and shadow evacuations, p=0.091.

Experienced evacuations in the past ten years
For natural disaster evacuations there is a significant positive association between this variable and shadow evacuations, p=0.021.

Level of community awareness with evacuation procedures
For technological hazard evacuations there is a marginally significant association between this variable and shadow evacuations, p=0.069. Half of the technological hazard evacuations in communities with high community awareness had shadow evacuations and half of the technological hazard evacuations in communities with low community awareness had shadow evacuations. Only 10% of the technological hazard evacuations in communities with medium community awareness had shadow evacuations.

C.2 Refusal to Evacuate

Whether or not anyone refused to evacuate was known for 47 evacuations in the data. In 26 cases (55.3%) an evacuation refusal took place and in 21 cases (44.7%) no early evacuation took place. A logistic regression model was used to test for association between shadow evacuation and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used to test for association between other variables in the dataset and shadow evacuation (Derr, 2000).

Community
Overall, there is a highly significant association between the type of community (i.e., urban, rural, and suburban) and evacuation refusal, p=0.0003. Furthermore there is a significant association after adjusting for hazard type, p=0.012. Eighty percent of evacuations that took place in rural areas had an evacuation refusal, 67% of evacuations that took place in a suburban area had an evacuation refusal, and none of the 9 evacuations that took place in a urban area had an evacuation refusal. For natural disaster evacuations there is not a significant association between this variable and evacuation refusal, p=1.0. For technological hazard evacuations this variable is highly significantly associated with evacuation refusal, p=0.0099. Fifty percent of urban technological hazard evacuations had an evacuation refusal, 62% of rural technological hazard evacuations had an evacuation refusal and none of the technological hazard evacuations had an evacuation refusal. None of the three evacuations due to terrorism had an evacuation refusal.

Did some people spontaneously evacuate before being told to do so?
Overall, there is a highly significant positive association between this variable and evacuation refusal, p=0.0004. Furthermore, after adjusting for hazard type there is a highly significant association, p=0.019. Eighty-six percent of evacuations where people spontaneously evacuated before being told to do so had evacuation refusals. Twenty-nine percent of evacuations where people did not spontaneously evacuate before being told to do so had evacuation refusals. For natural disaster evacuations there is not a significant association between this variable and evacuation refusal, p=0.27. For technological hazard evacuations this variable is significantly positively associated with evacuation refusal, p=0.041. Seventy-eight percent of technological hazard evacuations where people spontaneously evacuated before being told to do so had evacuation refusals. Thirty-one percent of technological hazard evacuations where people did not spontaneously evacuate before being told to do so had evacuation refusals.

Was public notified by a siren?
Overall, there is a highly significant association between this variable and evacuation refusal, p=0.0018. Furthermore, after adjusting for hazard type there is also a highly significant negative association, p=0.0044. Sixty-five percent of evacuations where public was not notified by a siren had an evacuation refusal. For those evacuations where the public was notified by siren, there were no reported refusals to evacuate. For natural disaster evacuations there is not a significant association between this variable and evacuation refusal, p=0.14. For technological hazard evacuations this variable is significantly negatively associated with evacuation refusal, p=0.045.

Hazard that led to evacuation
There is a highly significant association between the hazard that led to the evacuation and evacuation refusal, p=0.0043. Eighty-six percent of natural disaster evacuations had an evacuation refusal, none of the three terrorist evacuations had an evacuation refusal and 47% of the technological hazard evacuations had an evacuation refusal.

Elapsed time between start of hazard and decision to evacuate
There is a significant positive association between the elapsed time between the start of hazard and the decision to evacuate and evacuation refusal, p=0.021. However, after adjusting for hazard type this association becomes a marginally significant negative association, p=0.092. When the data are broken down by hazard type, there are no significant associations, p=0.78 for natural disaster evacuations and p=0.15 for technological hazard evacuations.

Was evacuation staged?
There is a significant positive association between the evacuation being staged and evacuation refusal, p=0.037. When the data are broken down by hazard type, there are no significant associations, p=0.46 for natural disaster evacuations and p=0.13 for technological hazard evacuations.

Were people told to use specific routes?
There is a marginally significant negative association between people being told to use specific routes and evacuation refusal, p=0.052. However, after adjusting for hazard type this association is no longer significant or marginally significant, p=0.12. When the data are broken down by hazard type, there are no significant associations, p=0.46 for natural disaster evacuations and p=0.37 for technological hazard evacuations.

Any special traffic problems encountered?
There is a marginally significant positive association between any special traffic problems encountered and evacuation refusal, p=0.055. However, after adjusting for hazard type this association is no longer significant or marginally significant, p=0.22. When the data are broken down by hazard type, there are no significant associations, p=1.0 for natural disaster evacuations and p=0.16 for technological hazard evacuations.

Were public shelters used?
There is a marginally significant positive association between public shelters being used and evacuation refusal, p=0.063. However, after adjusting for hazard type this association is no longer significant or marginally significant, p=0.65. All natural disaster evacuations in the sample used public shelters. There was not a significant association for technological hazard evacuations, p=0.65.

Any special problems regarding warning and subsequent citizen action?
For technological hazard evacuations there is a marginally significant positive association between special problems regarding warning and subsequent citizen action and evacuation refusal, p=0.073.

Were political boundaries crossed (i.e., more than one county or State involved)?
For natural disaster evacuations there is a marginally significant positive association between political boundaries crossed and evacuation refusal, p=0.077.

Population
For technological hazard evacuations there is a marginally significant negative association between population and evacuation refusal, p=0.094.

Time of day
For natural disaster evacuations there is a significant association between time of day and evacuation refusal, p=0.033. For all of the natural disaster evacuations in this sample that took place during the day there were evacuation refusals, for 33% of the natural disaster evacuations that took place in the night there were evacuation refusals.

Previous experience with the alerting mechanism
For technological hazard evacuations there is a marginally significant negative association between. Previous experience with the alerting mechanism and evacuation refusal, p=0.070.

Were multiple buildings used as shelters?
For technological hazard evacuations there is a marginally significant negative association between multiple buildings used as shelters and evacuation refusal, p=0.089.

Special characteristics
For natural disaster evacuations, there is a significant positive association between any special characteristics and evacuation refusal, p=0.033.

C.3 Early Evacuation

Whether or not people evacuated spontaneously before being told to do so was known for 43 evacuations in the data. In 22 cases (51.2%) an early evacuation took place and in 21 cases (48.8%) no early evacuation took place. A logistic regression model was used to test for association between shadow evacuation and each variable, and the results were adjusted for hazard type and tested for associations within each of hazard type (i.e., natural disasters and technological hazards). Given the relatively small sample size, exact tests were used to test for association between other variables in the dataset and shadow evacuation (Derr, 2000).

Did anyone refuse to evacuate?
Overall, there is a highly significant positive association between this variable and early evacuations, p=0.0004. There is also a significant positive association between this variable and early evacuations after adjusting for hazard type, p=0.019. When people refused to evacuate 75% of evacuations had early evacuations and when people did not refuse to evacuate 17% had early evacuations. For natural disaster evacuations there is not a significant association between this variable and early evacuation. For technological hazard evacuations this variable is significantly positively associated with early evacuations, p=0.041. For technological hazard evacuations when people refused to evacuate there were early evacuations 58% of the time and when people did not refuse to evacuate there were early evacuations only 15% of the time. None of the three evacuations due to terrorism had early evacuations.

Evacuation area
Overall, there is a highly significant positive association between this variable and early evacuations, p=0.0010. In general the bigger area evacuated the higher the likelihood that there will be early evacuations. After adjusting for hazard type there is no longer a significant association between evacuation area and early evacuations, p=0.27. For technological hazard evacuations this variable is marginally significantly positively associated with early evacuations, p=0.098. There is no significant association for natural disaster evacuations, p=1.0.

Hazard that led to the evacuation
Overall, there is a highly significant association between this variable and early evacuations, p=0.0022. Eighty-percent of natural disaster evacuations had early evacuations, none of the three terrorism evacuations had an early evacuation, and 39% of the technological hazard evacuations had an early evacuation.

Time to complete the evacuation
Overall, there is a highly significant positive association between this variable and early evacuations, p=0.0022. There is also a marginally significant positive association between this variable and early evacuations after adjusting for hazard type, p=0.072. In general the longer it takes to complete the evacuation the higher the likelihood that there will be early evacuations.

When the data are broken down by hazard type, there are no significant associations, p=0.56 for technological hazard evacuations and p=0.78 for natural disaster evacuations.

Shadow Evacuations (Did people evacuate from areas outside the designated evacuation area?)

Overall, there is a highly significant positive association between this variable and early evacuations, p=0.0029. There is also a highly significant positive association after adjusting for hazard type, p=0.0054. When there were shadow evacuations, 77% of the time there were also early evacuations. When there were no shadow evacuations only, 25% of the time were there early evacuations. For natural disaster evacuations there is not a significant association between this variable and early evacuation, p=0.13. For technological hazard evacuations this variable is marginally significantly positively associated with early evacuations, p=0.052. For technological hazard evacuations with shadow evacuations there were early evacuations 63% of the time and for technological hazard evacuations with no shadow evacuations there were early evacuations only 14% of the time.

Were public shelters used?

Overall, there is a highly significant positive association between this variable and early evacuations, p=0.0029. There is also a marginally significant positive association after adjusting for hazard type, p=0.061. Sixty-three percent of the evacuations where public shelters were used had an early evacuation; none of the evacuations where public shelters were not used had an early evacuation. There were no natural disaster evacuations where public shelters were not used. For technological hazard evacuations this variable is marginally significantly positively associated with early evacuations, p=0.061. For technological hazard evacuations when public shelters were used there were early evacuations 50% of the time and when public shelters were not used there were no early evacuations.

Type of community

Overall, there is a highly significant association between this variable and early evacuations, p=0.0040. After adjusting for hazard type there is not a significant association, p=0.24. For rural evacuations, 88% had early evacuations, for town evacuations, 86% had early evacuations and for city evacuations, only 35% had early evacuations. When the data are broken down by hazard type, there are no significant associations. Most of the evacuations that took place in a city were technological hazard evacuations, and overall, technological hazard evacuations were less likely to have early evacuations.

Population density during evacuation

Overall, there is a highly significant negative association between this variable and early evacuations, p=0.0045. There is also a significant negative association after adjusting for hazard type, p=0.017. For natural disaster evacuations this variable is significantly negatively associated with early evacuations, p=0.018, 100% of the low and medium density areas evacuated due to a natural disaster had early evacuations and none of the high population density areas evacuated due to a natural disaster had early evacuations. There is no significant association for technological hazard evacuations, p=0.25.

Elapsed time between start of hazard and decision to evacuate

Overall, there is a highly significant positive association between elapsed time between start of hazard and decision to evacuate and early evacuations, p=0.0048. However, after adjusting for hazard type this association is no longer significant, p=0.26. When the data are broken down by hazard type, there are no significant associations, p=0.68 for technological hazard evacuations and p=0.31 for natural disaster evacuations.

Emergency Operations Center (EOC) used
Overall, there is a significant positive association between EOC used and early evacuations, p=0.022. However, after adjusting for hazard type this association is no longer significant, p=0.23. When the data are broken down by hazard type, there are no significant associations for technological hazard evacuations, p=0.23, and no test could be carried out for natural disaster evacuations because all natural disaster evacuations used an EOC.

Was public notified by radio/TV?
Overall, there is a significant positive association between this variable and early evacuations, p=0.034. There is also a marginally significant positive association after adjusting for hazard type, p=0.080. When the public was notified by radio/TV, 68% of the time there were early evacuations. When the public was not notified by radio/TV, 33% of the time there was an early evacuation. When the data are broken down by hazard type, there are no significant associations, p=0.11 for technological hazard evacuations and p=0.42 for natural disaster evacuations.

Was public notified by multiple methods
Overall, there is a significant positive association between this variable and early evacuations, p=0.045. There is also a significant positive association after adjusting for hazard type, p=0.020. When the public was notified by multiple methods, 61% of the time there were early evacuations. When the public was not notified by multiple methods, 25% of the time there were early evacuations. For natural disaster evacuations there is a marginally significant positive association between this variable and early evacuations, p=0.066. For technological hazard evacuations there is not a significant association, p=0.19.

Any special traffic problems encountered?
Overall, there is a significant positive association between special traffic problems being encountered and early evacuations, p=0.045. However, after adjusting for hazard type this association is no longer significant, p=0.20. When the data are broken down by hazard type, there are no significant associations, p=0.26 for technological hazard evacuations and p=1.0 for natural disaster evacuations.

Major problems during re-entry?
Overall, there is a significant positive association between major problems during re-entry and early evacuations, p=0.048. However, after adjusting for hazard type this association is no longer significant, p=0.23. When the data are broken down by hazard type, there are no significant associations, p=0.36 for technological hazard evacuations and p=1.0 for natural disaster evacuations.

Were multiple buildings used as shelters?
Overall, there is a marginally significant negative association between this variable and early evacuations, p=0.062. There is a significant negative association after adjusting for hazard type, p=0.013. When multiple buildings were used as shelters, 42% of the time there were early evacuations. When multiple buildings were not used as shelters, 77% of the time there were early evacuations. For technological hazard evacuations there is a marginally significant positive association between this variable and early evacuations, p=0.057. For natural disaster evacuations there is not a significant association, p=0.38.

Has the community had any experience with the hazard?
Overall, there is a marginally significant positive association between the community having experience with the hazard and early evacuations, p=0.062. However, after adjusting for hazard type this association is not even marginally significant, p=1.0. When the data are broken down by hazard type, there are no significant associations for technological hazard evacuations, p=1.0 and that no test could be carried out for natural disaster evacuations because for all natural disaster evacuations the community had prior experience with the hazard.

Ethnicity, nationality of age important?
Overall, there is a marginally significant positive association between this variable and early evacuations, p=0.063. There is also a marginally significant positive association after adjusting for hazard type, p=0.091. When the data are broken down by hazard type, there are no significant associations, p=0.15 for technological hazard evacuations and p=1.0 for natural disaster evacuations.

Population
For population exact testing could not be computed. The p-values were estimated using the likelihood ratio test. Overall, there is a marginally significant positive association between this variable and early evacuations, p=0.065. There is also a marginally significant positive association after adjusting for hazard type, p=0.083. When the data are broken down by hazard type, there are no significant associations, p=0.87 for technological hazard evacuations and p=0.74 for natural disaster evacuations.

Were public buildings used as shelters?
Overall, there is a marginally significant negative association between this variable and early evacuations, p=0.070. There is also a significant negative association after adjusting for hazard type, p=0.024. When the data are broken down by hazard type, there are no significant associations, p=0.21 for technological hazard evacuations and p=0.23 for natural disaster evacuations.

Were people told to use specific routes?
Overall, there is a marginally significant positive association between people being told to use specific routes and early evacuations, p=0.096. However, after adjusting for hazard type this association is not even marginally significant, p=1.0. When the data are broken down by hazard type, there are no significant associations, p=0.14 for technological hazard evacuations and p=1.0 for natural disaster evacuations.

Were political boundaries crossed (i.e., more than one county or State involved)?
For natural disaster evacuations there is a marginally significant positive association between political boundaries being crossed and early evacuations, p=0.077.